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Training Command

NAVEDTRA 10390-D
December 1985
0502-LP-051-9520

Rate Training
Manual

Aviation Fire Control Technician 1 & C

Although the words "he," "him," and "his" are used sparingly in this manual to enhance communication, they are not intended to be gender driven nor to affront or discriminate against anyone reading *Aviation Fire Control Technician 1 & C*, NAVEDTRA 10390-D.

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Naval Education And Training Program Development Center

AVIATION FIRE CONTROL TECHNICIAN 1 & C

NAVEDTRA 10390-D

DEPARTMENT OF THE NAVY
CHIEF OF NAVAL EDUC AND TNG

1985 Edition Prepared by
AQCS Johnny R. Reeves

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PREFACE

This Rate Training Manual (RTM) and Nonresident Career Course (NRCC) form a self-study package that will enable Aviation Fire Control Technicians to fulfill the requirements of their rating.

Designed for individual study and not formal classroom instruction, the RTM provides subject matter that relates directly to the occupational standards for the AQ1 and AQC. The NRCC provides the usual method for satisfying the requirements for completing the RTM. The set of assignments in the NRCC includes learning objectives and supporting items that are designed to lead you through the RTM. The occupational standards are used as minimum guidelines in the preparation of this RTM. The complete list of occupational standards for the AQ rating are found in the *Manual of Navy Enlisted Manpower and Personnel Classifications and Occupational Standards*, NAVPERS 18068-D, Change 17.

This Rate Training Manual was prepared by the Naval Education and Training Program Development Center, Pensacola, Florida, for the Chief of Naval Education and Training. Technical review of the manuscript was provided by personnel from the Naval Aviation Logistics Center, Patuxent River, Maryland; NAMTRAGRUDET, NAS Miramar, San Diego, California; NAMTRAGRUDET, NAS Oceana, Virginia; and NATTC, NAS Memphis, Millington, Tennessee.

1985 Edition

**Stock Ordering No.
0502-LP-051-9520**

Published by
NAVAL EDUCATION AND TRAINING PROGRAM
DEVELOPMENT CENTER

UNITED STATES
GOVERNMENT PRINTING OFFICE
WASHINGTON, D.C.: 1985

THE UNITED STATES NAVY

GUARDIAN OF OUR COUNTRY

The United States Navy is responsible for maintaining control of the sea and is a ready force on watch at home and overseas, capable of strong action to preserve the peace or of instant offensive action to win in war.

It is upon the maintenance of this control that our country's glorious future depends; the United States Navy exists to make it so.

WE SERVE WITH HONOR

Tradition, valor, and victory are the Navy's heritage from the past. To these may be added dedication, discipline, and vigilance as the watchwords of the present and the future.

At home or on distant stations we serve with pride, confident in the respect of our country, our shipmates, and our families.

Our responsibilities sober us; our adversities strengthen us.

Service to God and Country is our special privilege. We serve with honor.

THE FUTURE OF THE NAVY

The Navy will always employ new weapons, new techniques, and greater power to protect and defend the United States on the sea, under the sea, and in the air.

Now and in the future, control of the sea gives the United States her greatest advantage for the maintenance of peace and for victory in war.

Mobility, surprise, dispersal, and offensive power are the keynotes of the new Navy. The roots of the Navy lie in a strong belief in the future, in continued dedication to our tasks, and in reflection on our heritage from the past.

Never have our opportunities and our responsibilities been greater.

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CHAPTER 1

ANTENNAS AND WAVEGUIDE PLUMBING

As an Aviation Fire Control Technician First Class or Chief, you may be required to supervise and instruct others in the maintenance of antennas and waveguide systems. Therefore, you need to understand antennas and waveguide principles and their application in aviation fire control equipment.

The fundamental principles of operation of antennas and waveguides are covered in *NEETS, Module 10* (NAVEDTRA 172-10-00-83) and are not discussed in this chapter. Therefore, you should review the material in the *NEETS, Module 10* and *Basic Electronics, Volume 2* (NAVPERS 10087-C) before continuing this manual. The material presented in this chapter relates to the antennas and waveguide systems used in aviation fire control equipment.

When you have finished this chapter, you will be able to

1. Recognize the characteristics of radar antennas.
2. Identify types of radar antennas, including the patterns they cover.
3. Recognize the applications of radar antennas.
4. Recognize the purpose and identify the methods of boresighting radar antennas.
5. Identify the various applications of boresighting.
6. Recognize the purpose for and identify the applications of microwave ferrites.
7. Recognize the purpose and identify the applications of ring duplexers.

ANTENNA CHARACTERISTICS

After an RF signal has been generated in the transmitter, there must be a means of radiating this signal into space. Also, there must be a means by which it may be intercepted (picked up) for use by the receiver. The device that fulfills both of these requirements is the **antenna**. The major purpose of a transmitting antenna is to convert the transmitter's RF energy into electromagnetic fields suitable for propagation (*NEETS, Module 10*) into space as efficiently as possible. The major purpose of the receiving antenna is to intercept the reflected electromagnetic fields from the target(s) and to change these fields into an RF signal that a receiver is capable of accepting and amplifying.

The process by which the RF energy is converted into electromagnetic waves and radiated into space is called **propagation**. Certain basic concepts of antenna propagation are included in *NEETS, Module 10*. These basic concepts should be thoroughly understood before continuing this chapter.

DIRECTIONAL PROPERTIES

One of the most important characteristics of a radar antenna is its directivity. An antenna may radiate energy equally well in all directions, or it may radiate in one specific direction better than other directions. All antennas are directional to a certain extent—some only slightly and others considerably more.

In aviation fire control radar, the directivity of an antenna is an important factor. An antenna that is highly directional radiates a maximum amount of energy in a specific direction, allowing maximum illumination of the target. Maximum illumination of the target or concentration of the radiated energy results in greater range capabilities of the radar set, better target definition, and greater accuracy in determining the position of the target. Also, an antenna receives from the same direction that it radiates. Therefore, the position of the antenna at the time of target reception is indicative of the relative target position.

There are several methods of controlling the directivity of an antenna that can be incorporated in its design. Most antennas found in aviation fire control radar use a parabolic dish-type device as a reflector for the radiated energy. It serves to reflect the radiated energy in much the same manner that light rays are reflected.

The degree of directivity of an antenna is referred to as its beam width. If an antenna is capable of radiating a cone of energy with a 3-degree apex, the antenna has a 3-degree beam width in both the vertical and horizontal planes.

The use of a narrow beam width results in more accurate target position determination. Most

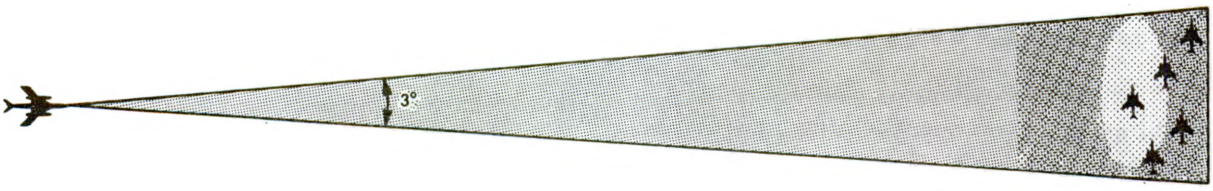

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Figure 1-1.—Pencil-type radiation pattern.

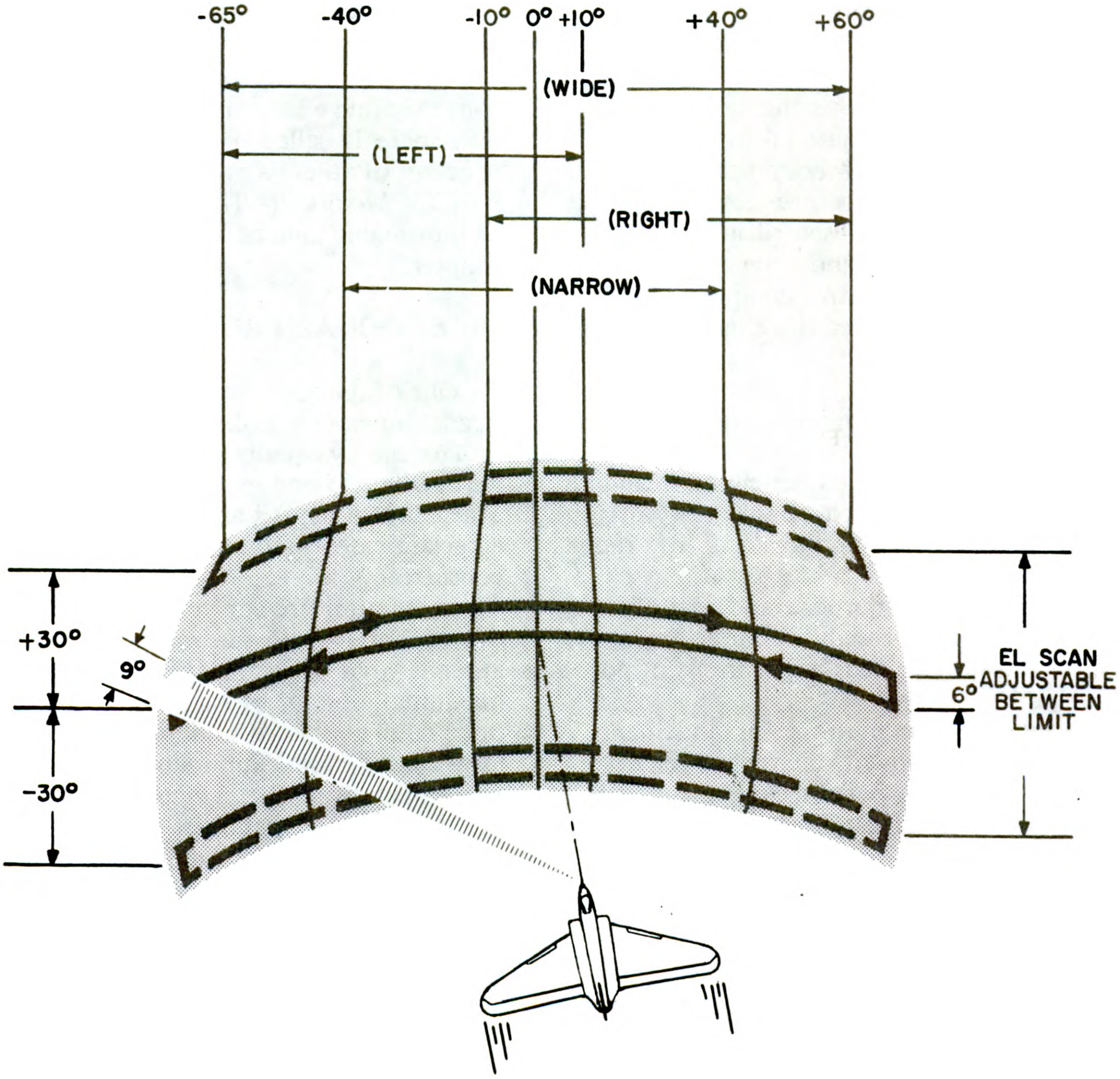

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Figure 1-2.—Conical beam sector scan.

fire control radar antennas radiate energy into space in narrow pencil-type beams or lobes. This is especially true of those radar antennas used in the detection of airborne targets. Figure 1-1 shows such a radar beam.

The larger the reflector (in terms of wavelength), the narrower the beam width of the reflector. However, the actual physical size is limited by the space available in the aircraft. The use of a smaller "dish" is possible by using higher frequencies. Thus, greater flexibility in locating the antenna in the aircraft is allowed, or, a larger dish (in terms of wavelength) may be used with an improvement in beam width.

In radar bombing equipment, covering a large surface area ahead of the bombing aircraft is desired. A beam that is narrow in the horizontal plane and wide in the vertical plane results in a narrow blade-shaped type of beam. Accurate directional characteristics in the azimuth plane are still maintained with this type of beam.

SCAN PATTERNS

Figure 1-2 is an illustration of a typical box-type intercept scan pattern. The antenna radiates a conical beam of approximately 9 degrees, which, when added to the 6-degree vertical nod, gives the antenna an automatic 15-degree elevation coverage as it scans back and forth in azimuth. By use of an operator's control, the antenna may be made to scan at any elevation angle within the limits of the equipment.

The degree of azimuth scan may also be selected by the operator in some equipments. In figure 1-2, the operator may select one of the following azimuth scan patterns:

1. Wide—approximately 130 degrees
2. Narrow—approximately 80 degrees
3. Left—approximately 75 degrees
4. Right—approximately 75 degrees

In many aviation fire control radar sets, the conical radar beam is caused to rotate (or nutate) as it scans a selected area. Figure 1-3 shows a nutated radar beam and the resultant coverage. The radar beam is caused to rotate in a circular motion at a specific rate by a spin motor. The spin motor mechanically drives the antenna radiator or antenna feedhorn in a circular motion and thus enlarges the illuminated area. (It should be remembered that the values shown in figure 1-3 are typical and vary with different equipments.)

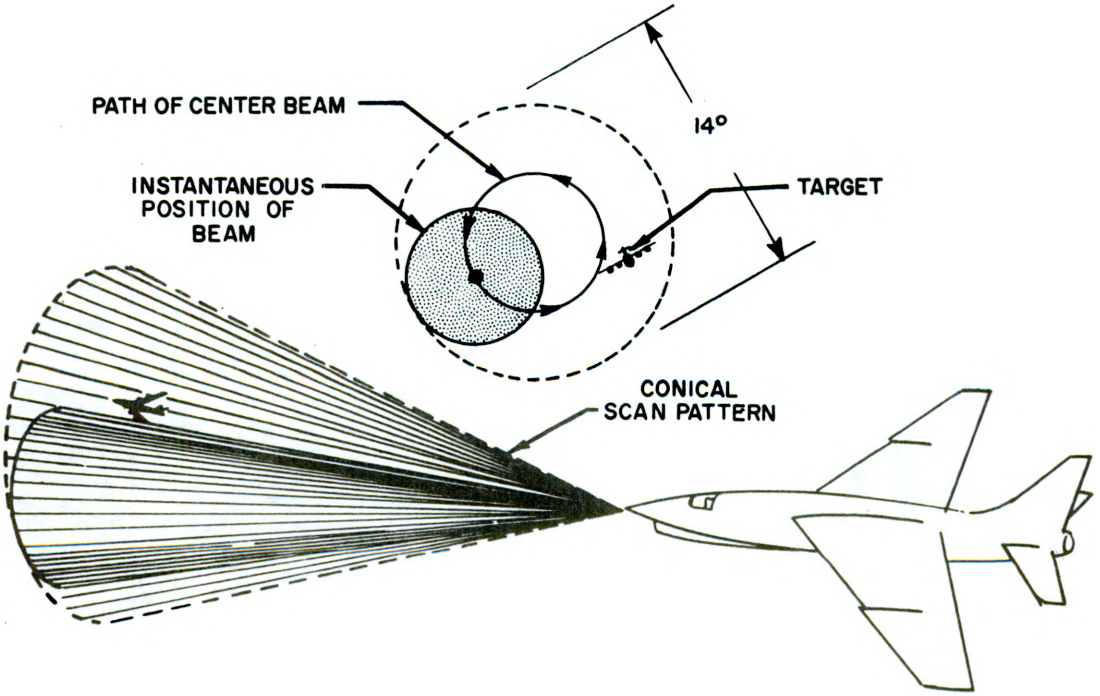

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Figure 1-3.—Rotating beam pattern.

Typical scan patterns found in aviation fire control equipment are shown in figure 1-4, view A and view B. Note that the antenna is also scanning vertically in figure 1-4, view B. This type of scan is almost always controllable to the extent that any sector within limits of the equipment may be scanned as desired. Antenna scan patterns are covered in more detail in chapter 4 of this manual.

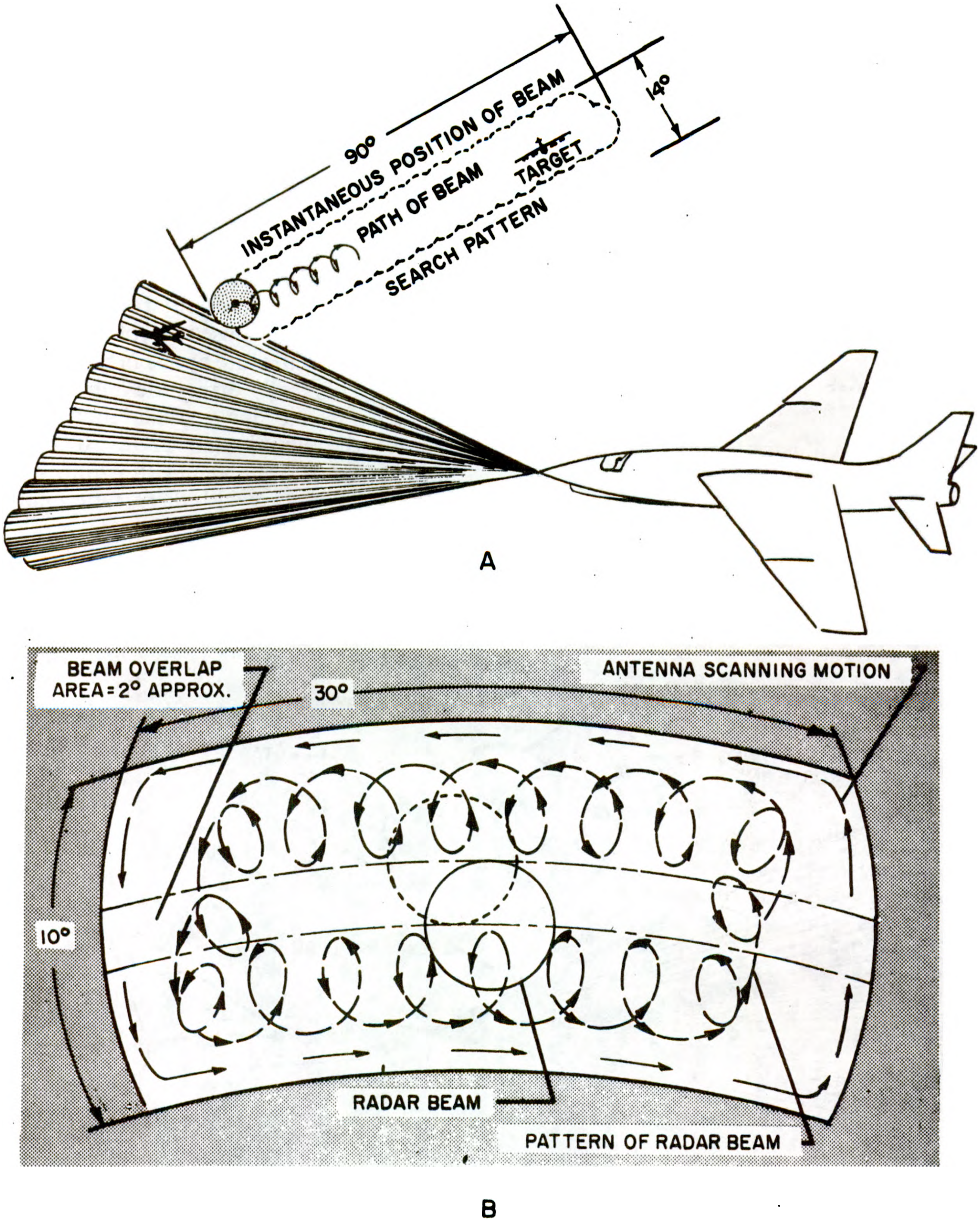

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Figure 1-4.—Antenna coverage patterns.

ANGULAR DETERMINATION

The measurement of the direction of a target from the radar system is usually given as an angular position. The angle may be measured from true north if the installation is stationary, or it may be measured with respect to the heading of the aircraft containing the radar set. The angle at which the echo signal returns is measured by using the directional characteristics of the radar antenna system.

The simplest form of antenna used for measuring azimuth or bearing is one that produces a single lobe pattern. The system is mounted so that it can be rotated. Energy is directed across the region to be searched, and the beam is scanned in azimuth until a return signal is picked up. The position of the antenna is then adjusted to give maximum return signal.

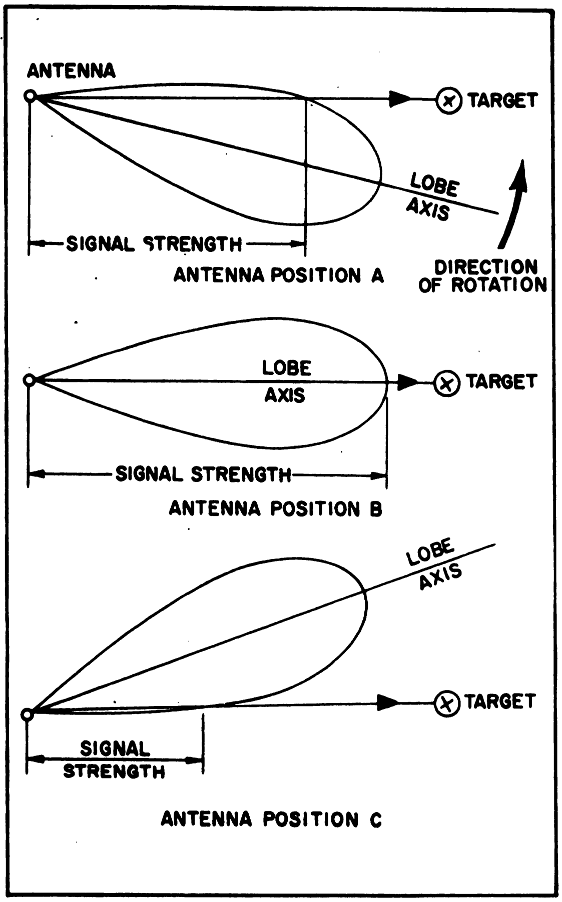

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Figure 1-5.—Relationship between beam axis and target bearing.

Figure 1-5 shows the receiving pattern for a typical radar antenna. Relative signal strength is plotted against the angular position of the antenna with respect to the target. Maximum signal is received only when the axis of the lobe passes through the target.

The sensitivity of the single lobe system depends upon the angular width of the lobe pattern. The operator adjusts the position of the antenna system for maximum received signal. If the signal strength changes rapidly with angular rotation, the accuracy with which the on-target position can be selected is great. Thus, in figure 1-6 there is little difference in the relative signal strengths of A and B. If the energy is concentrated into a narrower beam, the difference is greater and the accuracy is better.

In the single lobe antenna system, the signal strength varies more rapidly on the side of the lobe than near the axis. The greatest rate of change of signal strength per degree of rotation occurs between the angles that give 50 and 85 percent of maximum. Radar systems designed for gun laying for fire control require the highest possible accuracy in measuring azimuth angles. The multiple-lobe system achieves this accuracy by using two or more lobes to form the antenna system pattern.

The principle of the double lobe system is shown in figure 1-7. Here, two separate antennas whose lobe axes are displaced by some angular distance are used. The two lobe patterns intersect at one point only. This point is known as the crossover point. At the crossover point, equal signals are produced by the two antennas for this particular azimuth. At all other positions of the array, unequal signals are produced. Refer to figure 1-7. When the target is in position A, the echo signals strength received by lobe 1 is proportional to Y and that received by lobe 2 is proportional to X. If the antenna is rotated so that the target is in position B, the signal from lobe 1 decreases to an amplitude proportional to X, while that from lobe 2 rises to a value

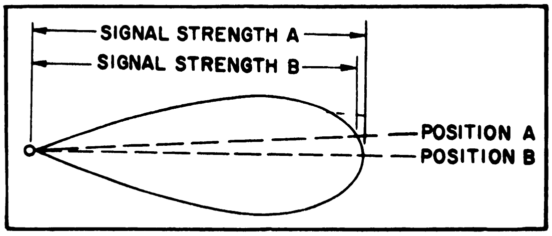

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Figure 1-6.—Accuracy of single lobe.

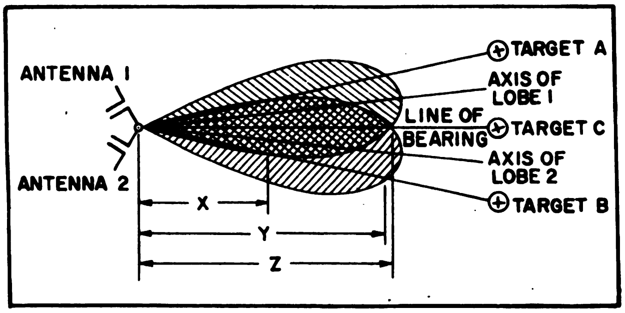

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Figure 1-7.—Double-lobe pattern.

proportional to Y. At position C, between these two positions of the antenna, the signals from the two lobes are equal and proportional to Z. At position C, the antenna system is on the bearing of the target.

The use of two lobes instead of a single lobe greatly increases the accuracy of azimuth measurement. The amount of increase depends upon the configuration of the antenna array. In addition to the greater accuracy of the double lobe, there is another advantage in the sense of direction available. If the antenna array is off target on the side of lobe 1 (fig. 1-7, position A), the signal received by lobe 1 is larger. Therefore, the antenna should be rotated toward the left until the signals become equal. When the amplitude of each signal is proportional to Z, the antenna is said to be on target.

The principles of operation of the two-lobe system, as used in aviation fire control, also apply to the four-lobe system. The four-lobe systems determines both azimuth and elevation angular information.

You may note that there is some loss in maximum range when the target is centered between the beams. This occurs only during track modes. Maximum range in search mode is unaffected. Since ranges involved in track modes are usually less than in search, some loss in maximum range can be tolerated.

TYPES OF ANTENNAS

There are many different types of antennas and antenna systems used in the field of airborne radar. In this manual, only those types peculiar to airborne fire control radar are discussed. There are essentially two basic types of antennas used in the specialized field of aviation fire control. One type is composed basically of one element (a radiating device), and the other is composed primarily of two elements (radiating and reflector).

COSECANT-SQUARED REFLECTORS

The cosecant-squared reflector is a modified version of the parabolic reflector, discussed in *NEETS, Module 10* and *Basic Eectronics,* Volume 2. Because of the variety of the applications of radar, widely different requirements must be met by different antennas. Antennas designed to produce special polarization effects or pattern shapes may differ greatly from those previously described. Airborne radar sets that are designed to scan a large area require a special beam shape. This beam should be narrow in the horizontal plane, but broad in the vertical plane (fig. 1-8). In addition, the particular area to be scanned must not be illuminated uniformly by the radar beam. Instead, the objects near the aircraft should be illuminated with less power than those farther away in the same sector because echo signals from nearby objects are stronger due to their closeness to the aircraft. On the other hand, a greater amount of power should fall on more distant objects in this sector since they would normally produce the weakest echoes. Thus, the radiated fields of the beam should be increased in strength at the greater distances. This type of pattern is used in radar bombing equipment. Figure 1-8, view A, shows some trigonometrical relationships of this situation.

If the aircraft is at point A (fig. 1-8, view A) and the target is at point B, the slant range **r** (straight-line distance from A to B) can be represented in terms of the aircraft altitude **h** and the angle of depression (θ) of the target as seen from the aircraft. This is represented by the formula

$$\frac{h}{r} = \sin\theta;\ r = \frac{h}{\sin\theta};\ r = h\csc\theta$$

Thus, the slant range is proportional to the cosecant of θ.

An antenna has been designed so that the field intensity pattern is also proportional to the θ. This antenna radiates a uniform electric field that causes the echo response of a nearby target to be approximately equal to that of a distant target having the same radar cross section (reflectivity). The equality of response is based on the concept of power density. Research has shown that power density is proportional to the square

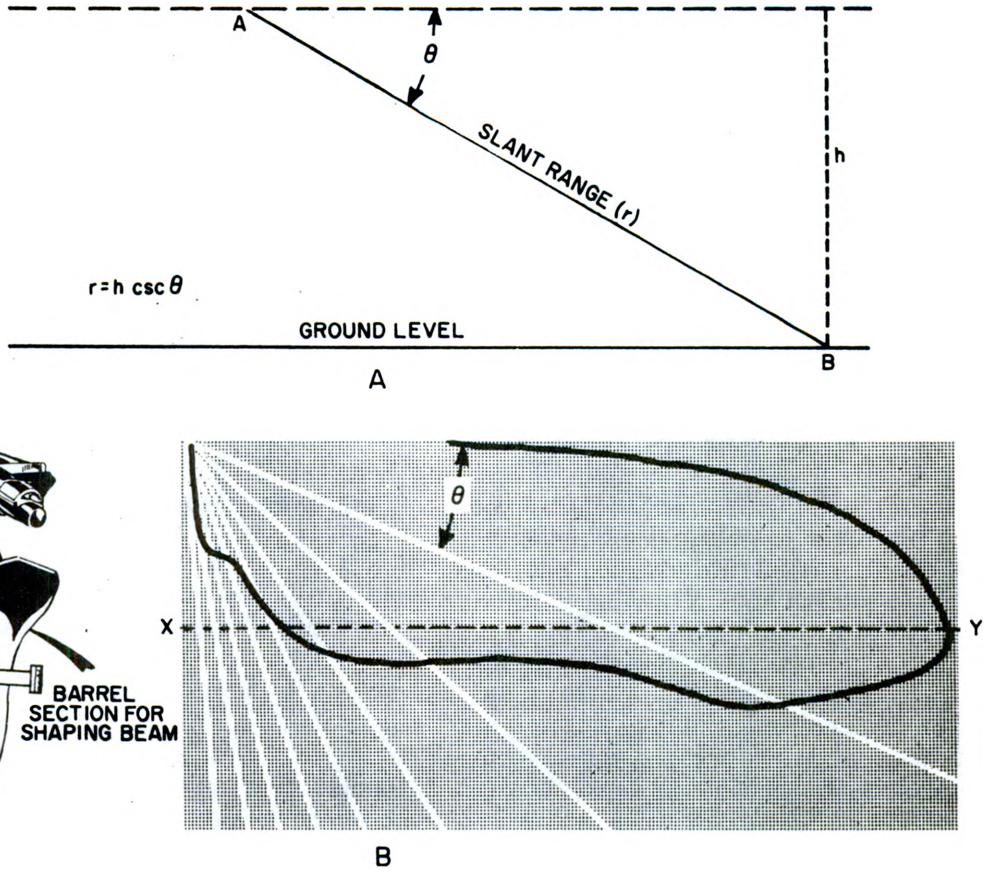

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Figure 1-8.—Cosecant-squared antenna and pattern.

of field intensity. This particular antenna, therefore, produces an electric field whose power density is proportional to the square of θ.

Remember, the RF signal strength is inversely proportional to the square of the distance from the source. Because of this, a balance of signal loss against signal gain is used in this antenna. As the slant range **r** (fig. 1-8, view A) increases, θ decreases and csc θ increases. The signal strength (power density) is inversely proportional to the square of **h** csc θ because the wave is RF energy. At the same time, the signal strength is directly proportional to the square of csc θ because of the antenna design. (Assume that **h** is constant.) The result is a net change of zero (theoretically) in the signal strength up to the maximum range of the transmitter. The antenna that produces this result is called the cosecant-squared antenna.

Figure 1-8, view B shows the special paraboloid reflector in which the top portion is bent forward to produce the cosecant-squared pattern. The pattern itself is also shown. Notice that this antenna produces a field of constant signal strength (bounded by the dotted line at ground level (line XY)) over a broad range of values of θ. This same type of antenna is also used (in an inverted position) on the land-based and shipboard systems for obtaining equal indications from aircraft at equal altitudes but different ranges.

ARRAY ANTENNAS

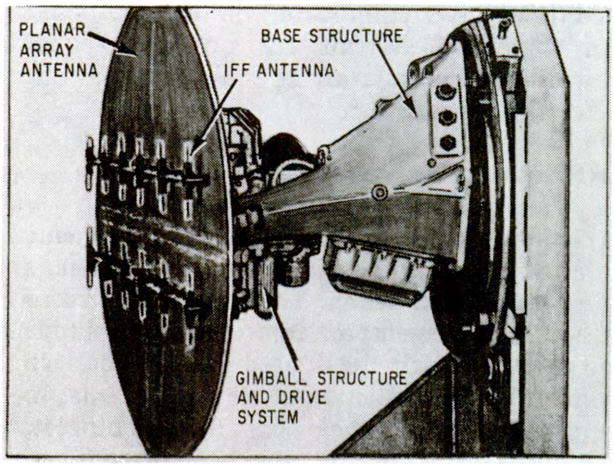
A number of individual radiating elements suitably spaced with respect to one another is called an array antenna. The signals applied to each of these elements are controlled in amplitude and phase to obtain the desired radiation pattern from the combined action of all the elements. In an array antenna, the elements may be dipoles, waveguide horns, or any other type of antenna. For an array to exist, it must consist of two or more elements. The maximum number of elements is limited only by its application.

The array antenna differs from the lens and reflector antenna. The lens and reflector apply the proper phase relationship to the wave fronts after it is radiated by the point-source feed. The shape of the wave front on leaving the feedhorn is spherical. The action of the lens or reflector converts it into a plane wave front. In the array antenna, the proper phase shifts are applied to the signal in the transmission lines before the signal is radiated.

The position of the main beam is determined by the relative phases between the elements. If the individual phases are fixed, the antenna radiation pattern is also fixed. Control of the beam formed by an array can be done either mechanically (by moving the entire array antenna structure) or electronically (by varying the phase relationship between the elements of the array).

Two common forms of antenna arrays are the linear array and planar array. A linear array has a number of elements arranged in a straight line in one dimension. A planar array is a two-dimensional display of elements arranged to lie in a plane.

The two-dimensional planar array (fig. 1-9) is the most versatile of all radar antennas. A rectangular aperture can produce a fan beam, and a square or circular aperture produces a pencil beam. Also many search and/or tracking beams can be made to be simultaneously generated with the same aperture. This technique is used in the track-while-scan radar discussed later in this chapter.



223.137

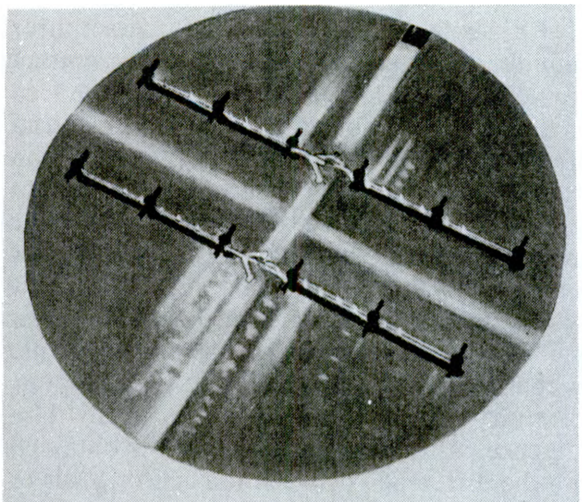
Figure 1-9.—Two-dimensional planar array antenna.

The planar array antenna group used in the F-14 aircraft is composed of an antenna, microwave circuitry, antenna servos, and a hydraulic power supply. A two-dimensional planar array antenna is shown in figure 1-9. The microwave circuitry couples and processes the transmitted and received RF energy. The antenna servos generate hydraulic drive signals and, together with the hydraulic power supply, drive the antenna.

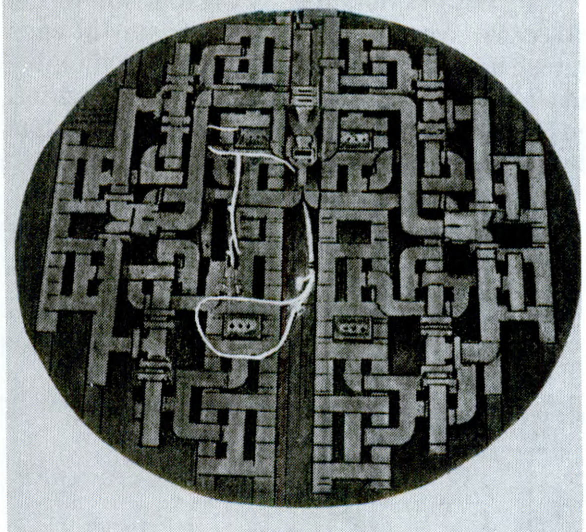
The planar array radiating panel consists of a sheet of parallel waveguides that radiate or receive energy by shunt element slots cut in the broad wall. The interslot spacing is 0.7 free space wavelength to optimize the radiation pattern and gain characteristics. The width of the radiating waveguide is chosen so that the slots are spaced 0.5 wavelength apart to achieve proper in-phase illumination. Several adjacent radiating waveguides are connected by a waveguide, which in turn has a single RF energy feed point. These waveguides comprise a module. The size of the module is determined by geometrical considerations, but it must be kept small for large bandwidth antennas.

The corporate feed of the planar array distributes energy (on transmission) to or collects energy (on reception) from the various modules in each quadrant. The structure consists of thin-walled sections of waveguides and H-plane power dividers (tees) arranged to provide a single input and 19 outputs per quadrant on transmission. Each output is interfaced with the input port of a module and therefore provides for the RF illumination of a small section of the overall antenna aperture.

In order to obtain uniform phase illumination for the aperture distribution desired, the electrical lines from the input to the corporate feed to each module are designed to have equal lengths. In order to obtain the desired amplitude illumination, the power division ratios of the tees are designed so that the proper amount of input power is fed to each of the several output ports. The power required at the output ports is, in turn, determined by the number of radiating slots to be fed in that module and by the position of the module in the array.



(A) FRONT VIEW



(B) REAR VIEW

223.138

Figure 1-10.—Planar array.

Front and rear view photographs of the planar array are shown in figure 1-10. The separate elements of the planar array (such as the radiating waveguide sheet, feed guides, and corporate feed assemblies) are assembled using conductive and structural adhesives. The conductive adhesives are required to assure proper RF coupling between the sections without any RF leakage. An aluminum filled conductive adhesive is used in the fabrication of the planar array. Because of this, the possiblility of corrosion caused by the galvanic potential between dissimilar metals is substantially reduced.

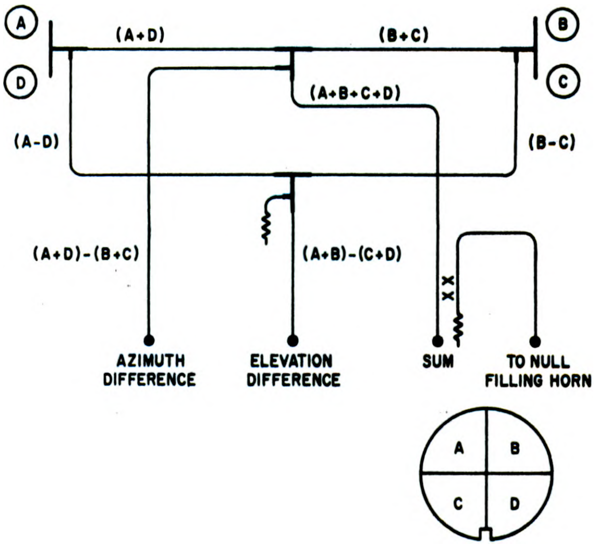


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Figure 1-11.—Planar array, sum and difference schematic.

A schematic of the planar array sum and difference network is shown in figure 1-11. During transmission periods, RF energy is introduced at the sum port. For plane wave signals arriving from off boresight, however, phase differences occur between the signals at the ports of the four quadrants. These phase differences are used in phase monopulse processing. The vector processing of these signals in the sum and difference network not only produces an additive sum, but also a differential sum (difference signal) in each of the two principal planes. The amplitude and phase of the difference signals relative to that of the sum signal contain the information required for angle tracking.

ANTENNA APPLICATIONS

The purpose of an airborne fire control radar system is to supply to a compute (human or electronic) accurate range and pointing angle (directional) information concerning a target for use in the firing of the aircraft's armament. While precise measurement of the range can be made by timing the radar echo, the pointing accuracy of a simple radar can be basically no better than the beam width of the antenna. The antenna beam width is approximately λ/D (radius, where λ is the wavelength of the radiation, and D is the antenna width or, for a paraboloid, the diameter). As the beam width becomes narrower, the pointing angle accuracy improves. The basic method of obtaining the higher accuracy may be termed *lobe comparison*, and the numerous variations of the method may be classified as simultaneous and time sequential.

SIMULTANEOUS LOBE COMPARISON SYSTEMS (MONOPULSE)

In the simultaneous lobe comparison system, complete target position information is obtained on each pulse of the radar set. For this reason the system is commonly called monopulse.

The monopulse antenna derives signals from the target echo that gives the range of the target and its direction relative to the axis of the antenna. Figure 1-12 shows a three-channel monopulse radar system. There are three waveguide terminals in this system: one for the transmit and range signal reception and one each for azimuth and elevation error signal reception. The RF signals which appear at these three terminals are used to provide the dc pointing error voltages. The signals picked up by the feed apertures are combined so their sums and differences are obtained. Two types of radiation patterns result in each plane: a sum pattern (fig. 1-13) and a difference pattern (fig. 1-14). The sum signal is used for search operations and gives the range of the target. The sum pattern is obtained by the in-phase addition of the echo signal received by the two apertures in one plane. It is characterized by a main lobe of considerable directivity along the antenna axis. The difference pattern for any one plane is obtained from the difference between the echo signals as received by each of the apertures in that plane. From these signals, the azimuth and elevation error signals are obtained by comparison of the difference signals with the sum signal in each plane. The difference pattern has two main lobes and a null on axis. The main lobes are symmetrical and equal for a difference pattern plotted in power; however, the fields associated with the two lobes are 180 degrees out-of-phase. Also, the RF voltage appearing at the antenna error channel

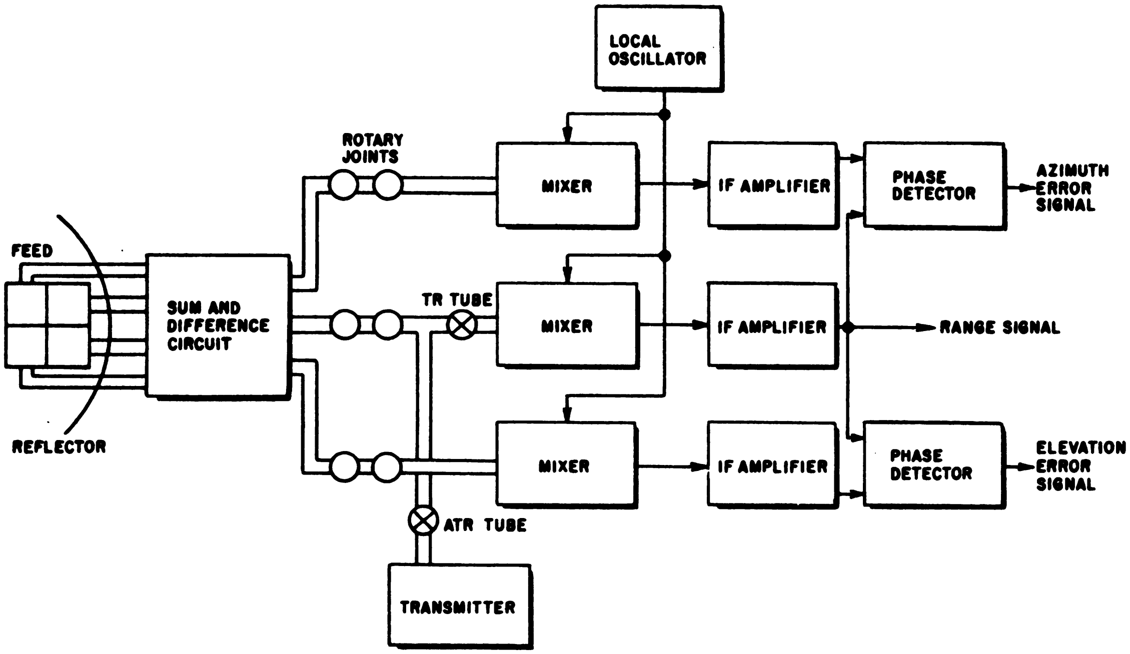

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Figure 1-12.—Three-channel monopulse radar system.

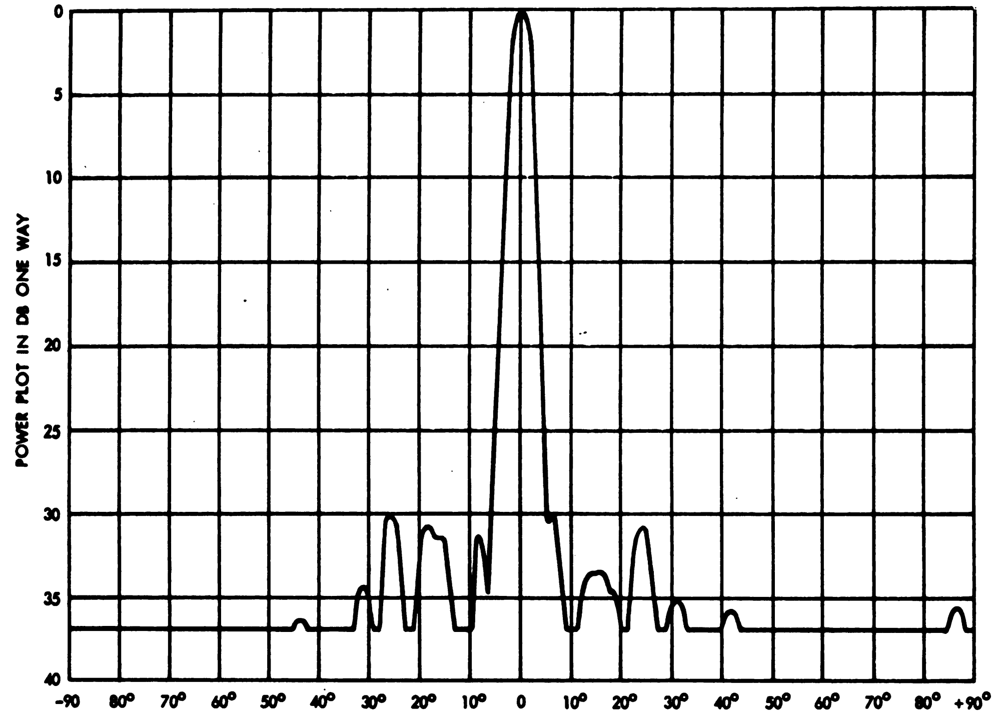

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Figure 1-13.—Typical sum radiation pattern of monopulse antenna.

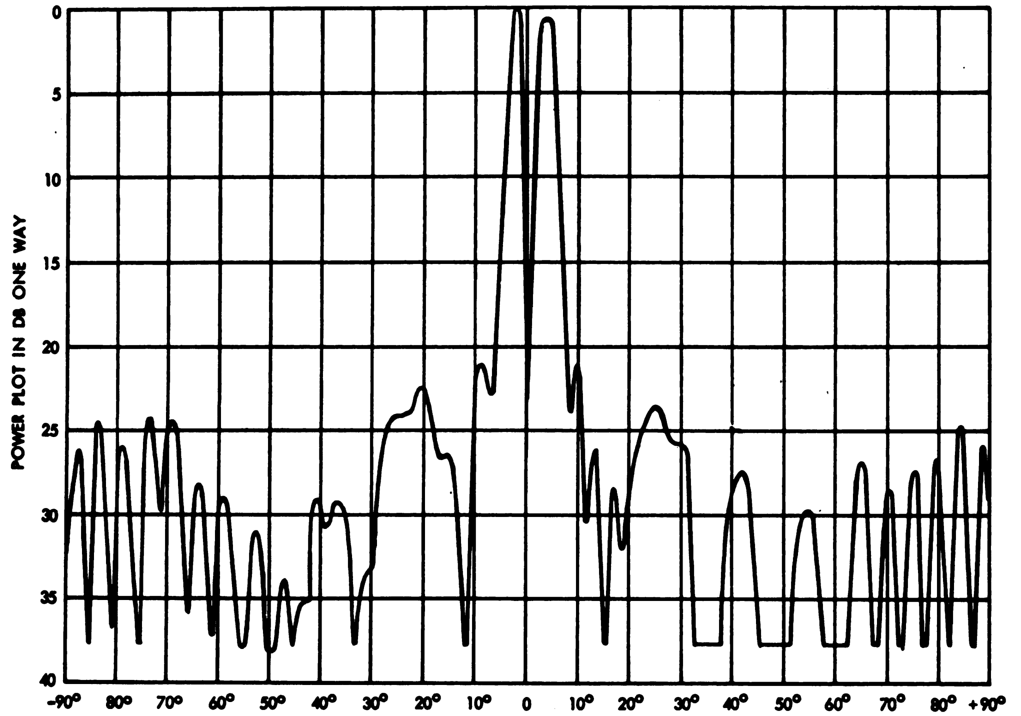

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Figure 1-14.—Typical difference radiation pattern of monopulse antenna.

terminals varies with angle (fig. 1-15). (This description assumes perfect symmetry in the antenna.)

The nonlinear response of the radar receiver with its automatic gain control modifies the error characteristic so that the final dc error signal that controls the antenna pointing servos varies somewhat with pointing error (fig. 1-16). The pointing accuracy of the system is dependent upon the steepness of the overall antenna characteristic near zero. If the noise in the system has an amplitude as shown in figure 1-16, small error signals will be masked by the noise, and the antenna will point erratically between angles $+\beta$ and $-\beta$. A steeper characteristic decreases this error. The steepness of the overall characteristic is proportional to the slope of the antenna difference voltage characteristic, and it is desirable to design the antenna to maximize this slope. The error characteristic is an intrinsic feature of the antenna and depends upon the aperture illumination.

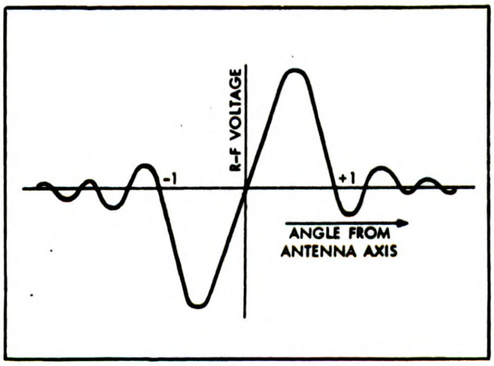

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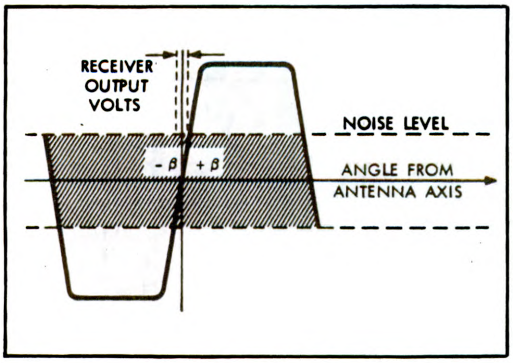
Figure 1-15.—RF voltage at error terminal of antenna.



223.144
Figure 1-16.—DC error voltage at servo input.

The relative level of the noise (fig. 1-16) depends upon the signal-to-noise ratio. The signal-to-noise ratio in the final error signal output determines the pointing accuracy of the system. The overall signal-to-noise ratio is determined by the RF signal at the mixer. This signal depends upon both the antenna transmitting and the error receiving characteristics. The received wave is a reflection of the transmitted wave and is proportional to the gain of the antenna transmit channel. Thus, a true measure of the antenna error sensitivity must be a function not only of the slope of the antenna error voltage characteristic but also of the antenna transmit channel gain.

Monopulse systems are usually classified as phase comparison, amplitude comparison, or phase amplitude comparison, depending upon the characteristics of the antenna.

Phase Comparison System

In the phase comparison system, there are always two or more apertures in each plane that are fed independently. The target echoes picked up by the two apertures are equal in amplitude because the apertures are oriented together. However, when the target is not on the axis of the antenna, the echoes picked up by the apertures differ in phase since one aperture of the antenna is closer to the target than the other.

Amplitude Comparison System

In the amplitude comparison system, at least two components of the feed aperture are aligned in each plane. They are generally smaller than those of the phase comparison type since there is no need for size or geometric separation to pick up several phases of the incident wave. The target echo excites each aperture differently, and pointing information is derived from the resulting amplitude difference.

Phase Amplitude Comparison System

In the phase amplitude comparison system (a combination of the phase comparison and phase amplitude comparison types), error signals are obtained by phase comparison in one plane and by amplitude comparison in the other.

MONOPULSE SYSTEM ERRORS

Pointing errors can arise in two distinct ways in any of the monopulse antenna systems. Phase or amplitude discrepancies in the received signals give rise to pointing errors. These errors result from asymmetries in the feed structure or from radome refraction. A second contribution to the pointing error arises from the combined effects of the radome error and the asymmetries and of phase errors between the parallel receiver channels that are required in a monopulse system. Signal errors in phase or amplitude are always present to some degree since the feed structure and the radome cannot be perfect. Similarly, phase discrepancies between receiver channels are generally present. However, for satisfactory system performance, both sources of pointing error must be minimized. In fact, the design of IF amplifiers with satisfactory phase characteristics over a large dynamic range constitutes one of the major problems in a monopulse system.

A constant phase distortion causes the antenna pointing angle to deviate a fixed distance as long as the frequency is constant. However, at a constant frequency, variations occur in the errors introduced by amplitude distortions in combination with phase errors between receiver channels.

In itself, some shift is not detrimental (as long as the frequency is constant) since it merely defines a new pointing axis. The position of the new axis, however, varies with frequency. It is the shift of the pointing axis with frequency that is important. The phase error between feeds may result from structural asymmetries in the feed, or it can result from radome effects. Since the phase errors caused by the radome vary as the antenna scans, a variable shift in the pointing axis then results, even with a fixed frequency. The major sources of error for both phase- and amplitude-comparison monopulse systems are in the feed system. These sources are as follows:

- The primary errors of the phase comparison system are phase errors. The secondary errors are amplitude errors (in front of the sum and difference circuits).

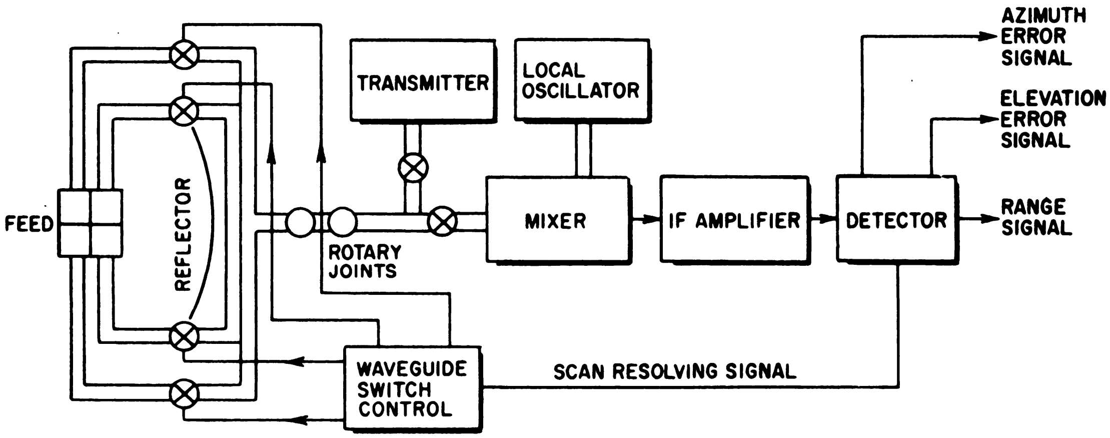
- The primary errors are amplitude errors. Secondary errors are phase errors in the amplitude comparison systems.

- Both systems experience phase errors between receiver channels.

TIME SEQUENTIAL LOBE COMPARISON SYSTEMS

The time sequential classification includes conical scan and sequential lobing system. Conical scanning was discussed earlier under scan patterns. The following paragraphs compare conical scanning with sequential lobing.

A time sequential radar system that provides only four positions in rotation is a sequential lobing radar system (fig. 1-17). The sequential lobing antenna has four feed apertures. By means of waveguide switches, these four apertures may be used individually in sequence to provide (without motion) the same result as conical scan. This is done at much higher scanning speeds than are possible mechanically (conical scan). The construction of some sequential lobe comparison systems inherently provides a further advantage over conical scan. All four apertures transmit



223.145

Figure 1-17.—Sequential lobing radar system.

simultaneously, while only one receives at a time. In this way, the peak of the transmitted aperture beam is on the crossover axis. This gives a larger target reflection than the conical scan system can give because the beam peak is displaced from the crossover axis.

COMPARISON OF MONOPULSE WITH TIME SEQUENTIAL SYSTEMS

Both the conical scan and sequential lobing systems have an essential characteristic. They measure echoes received at different times (fig. 1-18). On the other hand, the monopulse systems derive all range and pointing information from each single pulse echo (fig. 1-19 and 1-20). Fire control antennas are classified as simultaneous lobe comparison or time sequential lobe comparison because of the significant advantage of monopulse. Since time sequential lobing entails comparison of two echoes separated in time, changes in the reflective properties (scintillation) of the target for fluctuation in transmitted power can cause false error signals vulnerable to certain types of jamming. Higher scanning speed is obtainable by sequential lobing with waveguide switches rather than mechanical motion. The monopulse derives complete information from each pulse; thus, it is not susceptible to these effects.

An advantage monopulse enjoys over conical scan, although not necessarily over sequential lobing, is a greater overall angular sensitivity because the target is tracked at the peak of the transmitted beam. In conical scan, the target is

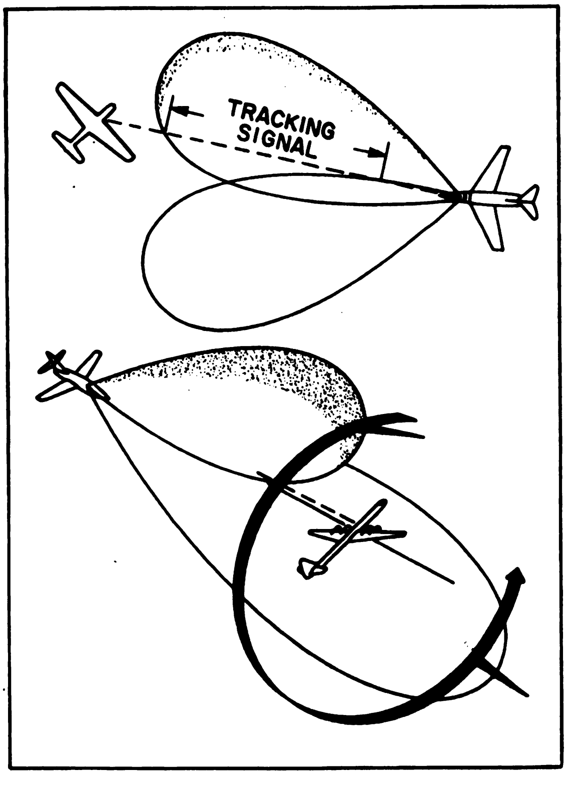


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Figure 1-18.—Typical fire control antenna beam—conical scan.

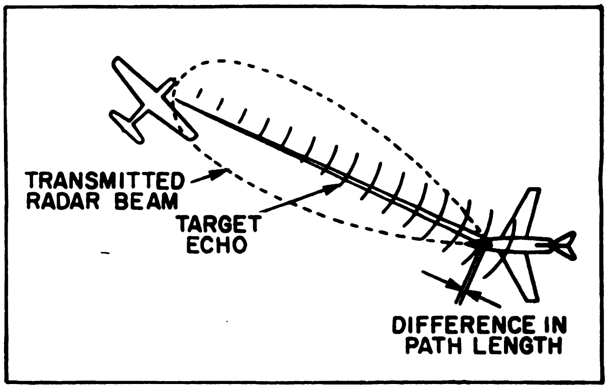

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Figure 1-19.—Typical fire control antenna beam—phase comparison monopulse.

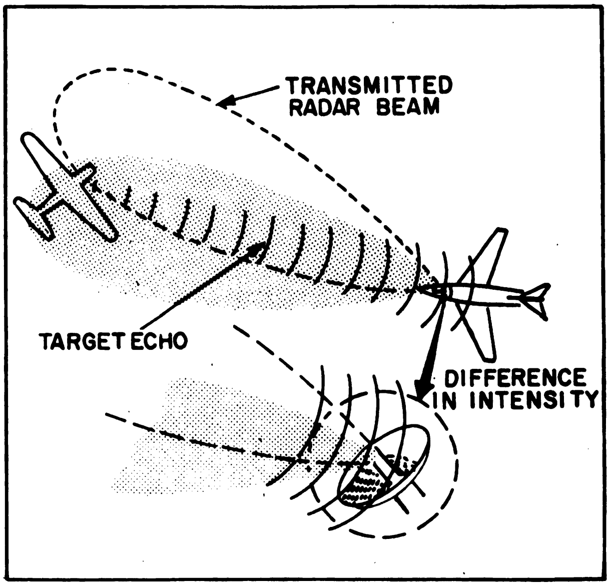

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Figure 1-20.—Typical fire control antenna beam—amplitude comparison monopulse.

tracked at the beam crossover, which is usually near the half-power point. The voltage sensitivity is essentially equal for both monopulse and conical scan antennas, but the overall angular sensitivity is less for the conical scan because of the weaker echo. The sequential lobing antenna can be designed to track the target at the peak of the transmitted beam and can avoid the power loss inherent in the conical scan. However, with a sequential lobing system, the RF noise produced in the received signal by existing lobe switching tubes is a major disadvantage.

In a conical scan antenna, input impedance varies with rotation of the scanning mechanism. The changing load presented to the magnetron causes fluctuations both in frequency and in power. A unilateral device, such as a ferrite gyrator, is necessary to overcome this problem. The input impedance of a monopulse antenna remains essentially constant, since there are no moving elements except the rotary joints.

Mechanically, the monopulse antenna is somewhat more complex than the conical scan type; but, there are no moving parts in the antenna proper. Since the antenna feed has no bearings or drive mechanisms, the monopulse system is less subject to mechanical breakdown. Pressurization may be easier. However, the additional rotary joints which are necessary if receive components are not mounted on the antenna are an added complexity. Although monopulse antennas vary in weight from type to type, they compare favorably with the conical scan when the weight of the spin motor and resolver is considered.

In sequential lobe comparison and conical scan systems, the pointing error information appears as an amplitude modulation of the received signal. Only one channel (involving one rotary joint in each gimbal axis, one mixer, and one IF amplifier) is necessary to carry this information. In a sense, this single channel is time-shared. On the other hand, the monopulse system derives complete pointing information from each pulse echo. Therefore, it cannot time-share one channel, but requires two or three. The multiplicity of receiver components and rotary joints adds weight and complexity and tends to decrease the electrical reliability. The additional rotary joints may be avoided by mounting some receive components on the antenna, although this arrangement adds inertia to the antenna and requires the use of flexible cables. The decision of whether to suffer the additional rotary joints or to avoid them by placing receive components on the antenna is an involved one that must be reached for each particular application.

TRACK WHILE SCAN

The use of the digital computer has greatly increased the versatility of aviation fire control systems. With the use of a digital computer, interpolative tracking is possible. Interpolative tracking provides for the tracking of more than one target with the maximum targets being limited by the capacity of the digital computer. This technique is called *track-while-scan.*

During the track-while-scan mode, a search pattern may be used as shown in figure 1-21. In this pattern, each circle represents a monopulse cluster. Any detections that occur off the boresight or center of a monopulse cluster result in angle-deviated monopulse signals. These radar observations of range, range rate, elevation, and azimuth of targets within the scan pattern must be sorted into groups of observations that presumably have been obtained from the same target. A track is a set of observations that have been so grouped, and the sorting process applies new observations with the track. Past observations of a target are smoothed and used to predict its location at the time of the next observation.

As previously mentioned, the digital computer determines the number of targets that can be tracked, which may be as high as 20. If the attacking aircraft is carrying six missiles, the track-while-scan radar can guide all six missiles

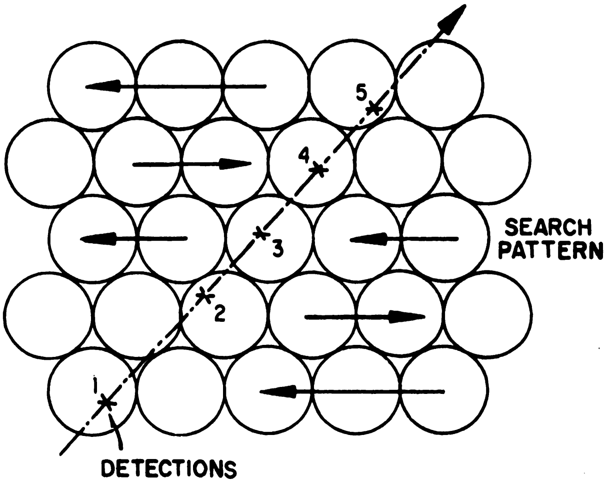

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Figure 1-21.—Track while scan search pattern.

to six different targets. The targets chosen are usually the ones that are the nearest to the attacking aircraft. However, any target that is being tracked can be attacked.

ANTENNA BORESIGHTING

In this section, a discussion of the purpose, methods, and application of antenna boresighting is presented.

PURPOSE

The purpose of boresighting aircraft weapon systems is to establish a relationship among the flight attitude of the aircraft, the bore axes of the armament, and the axis along which the sighting is projected. The theory of boresighting involves analyzing pertinent ballistics and mechanical data in establishing the relationship between the sight line of the aiming device and the trajectory of the projectile being fired or launched in order to predict its mean point of impact at predetermined ranges. No weapons system can do its job accurately unless it is properly aligned with the weapon with which it is used. The weapon system and weapon must be made to function together. This technique of making them function together is called boresighting.

The primary reference when boresighting the entire aircraft is the zero-zero radar axis. This is the line in space along which the radar antenna points when tracking a target with zero azimuth and elevation gimbal angles.

METHODS

The first method of boresighting is called *full boresight*. Full boresight provides a complete RF and optical boresight. As a result, the state of alignment of the radar axis and optical axis is determined. The applicable maintenance instruction manual (MIM) should be consulted for the step-by-step procedure.

The second method of boresighting is called *radar silence boresight*. Radar silence boresight is the same as full boresight except that a telescope fixture is used as the only reference. This procedure can be used whenever it is impossible to radiate. It is also used when there is insufficient time for the full procedure.

The third method of boresighting, called *fast boresight*, is only for use with the director portion of the aircraft weapons system. The boresight method can be used only when the aircraft has been boresighted previously using the full procedure with a given antenna. Then, the fast boresight method can be used to establish the electrical boresight of the director.

For the purposes of this rate training manual, the boresighting procedure is carried out in two phases—electrical boresighting and harmonization. Electrical boresighting is the procedure used to bring the radar antenna's RF axis into a parallel relationship with its optical axis. This procedure must be carried out before the harmonization procedure.

Harmonization is the procedure used to bring the radar antenna's optical axis into a parallel relationship with the aircraft armament datum line. Harmonization also extends to the adjustment of the guns and optical sight unit.

Electrical boresighting requires RF energy to be radiated. However, in most aviation fire control radars, satisfactory harmonization can be done without radiation, provided the antenna's optical axis is in proper agreement with the RF axis of the antenna. Once done, the electrical boresight should remain valid as long as no portion of the antenna structure is damaged, replaced, repaired, or the adjustments disturbed.

BORESIGHTING APPLICATIONS

The type of boresighting used depends upon many factors such as the type of mission, availability of equipment, and time the aircraft is available.

Short-Range Boresighting

Short-range boresighting is used where space is at a premium such as on an aircraft carrier. In past years, short-range boresighting was not considered the best method and was only used when necessary.

Modern aircraft can now be accurately boresighted using the short-range equipment provided by the aircraft manufacturer. Figure 1-22 shows a short range boresight kit installed on an aircraft. The equipment is installed on the structure of the aircraft, which eliminates the need of jacking or leveling. With the boresight fixture correctly installed on the aircraft, the AQ can boresight the radar, the AO can boresight the

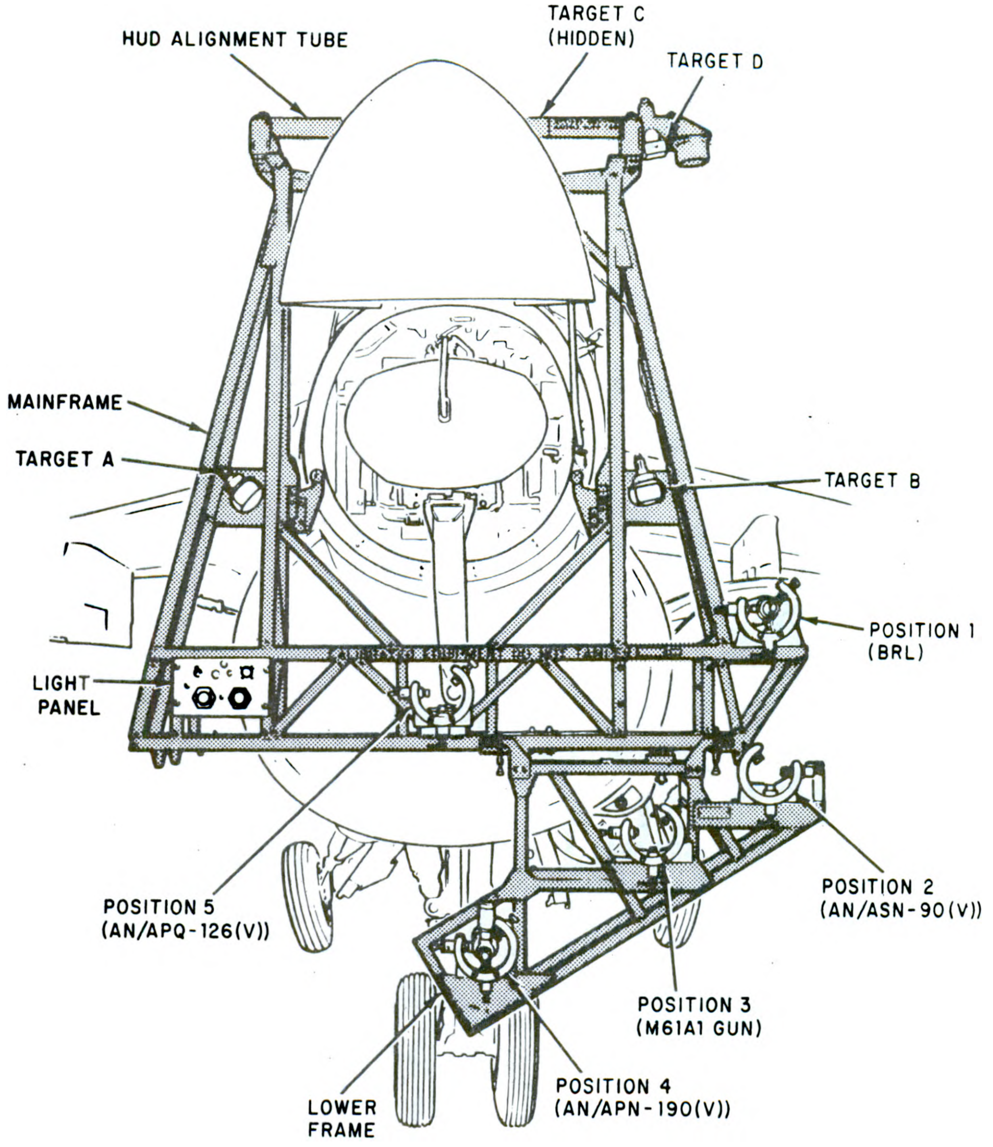

Figure 1-22.—Short-range boresighting equipment.

guns, and the AT can align the navigation equipment.

The equipment is considered to be a precision instrument and must be calibrated by a naval air rework facility (NAVAIREWORKFAC). To maintain its calibration, you should exercise care when using this equipment.

Each type of aircraft is provided with its own short-range boresighting equipment. The procedures for installation and alignment of the aircraft equipment are contained in the MIM for that particular type of aircraft.

Far Field Antenna Boresighting

When the far field antenna boresighting method is used, the antenna under test is boresighted to a source feedhorn by receiving radiated energy that is being transmitted by the source feedhorn. For these antennas, a far field antenna test range normally requires at least 50 feet between the radar antenna

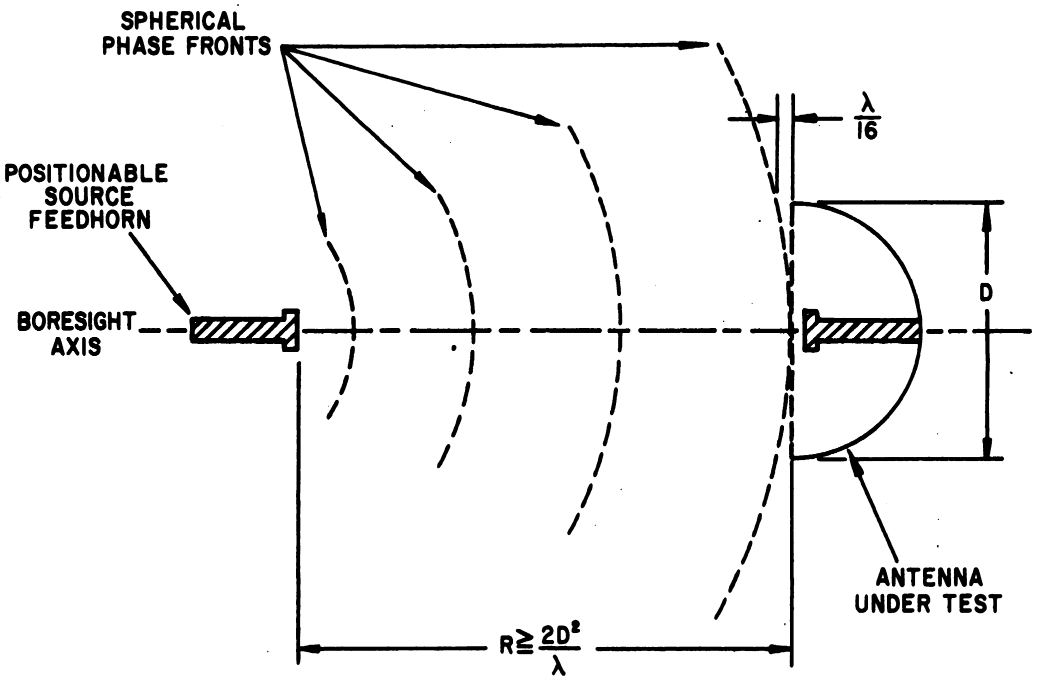

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Figure 1-23.—Far field measurements conditions.

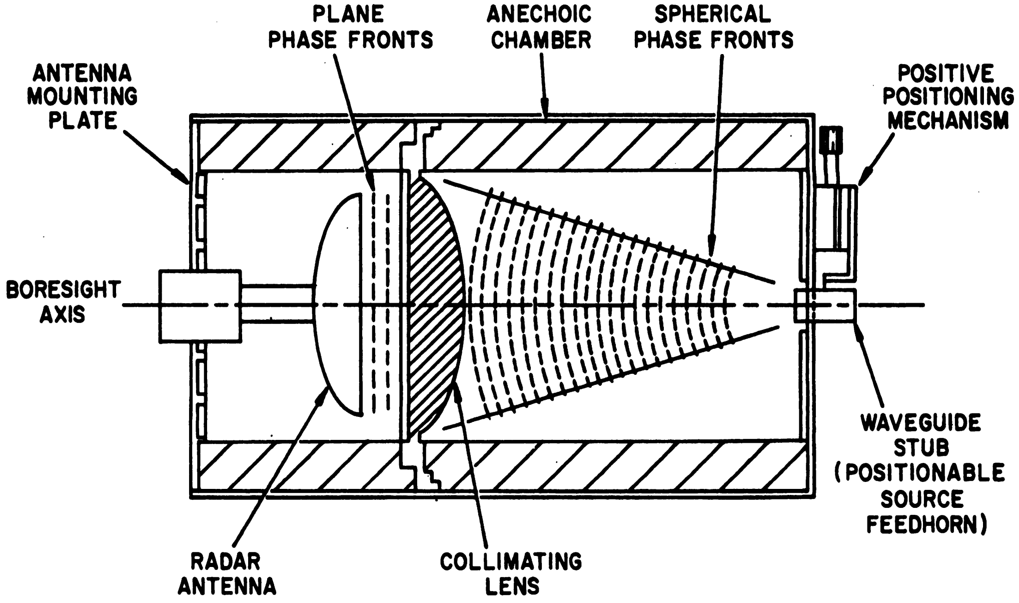

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Figure 1-24.—Lens chamber assembly.

under test and the radiating antenna source. (See fig. 1-23.) The distance can be calculated using the formula

$$R \geqslant \frac{2\,D^2}{\lambda}$$

where

T = range

D = diameter

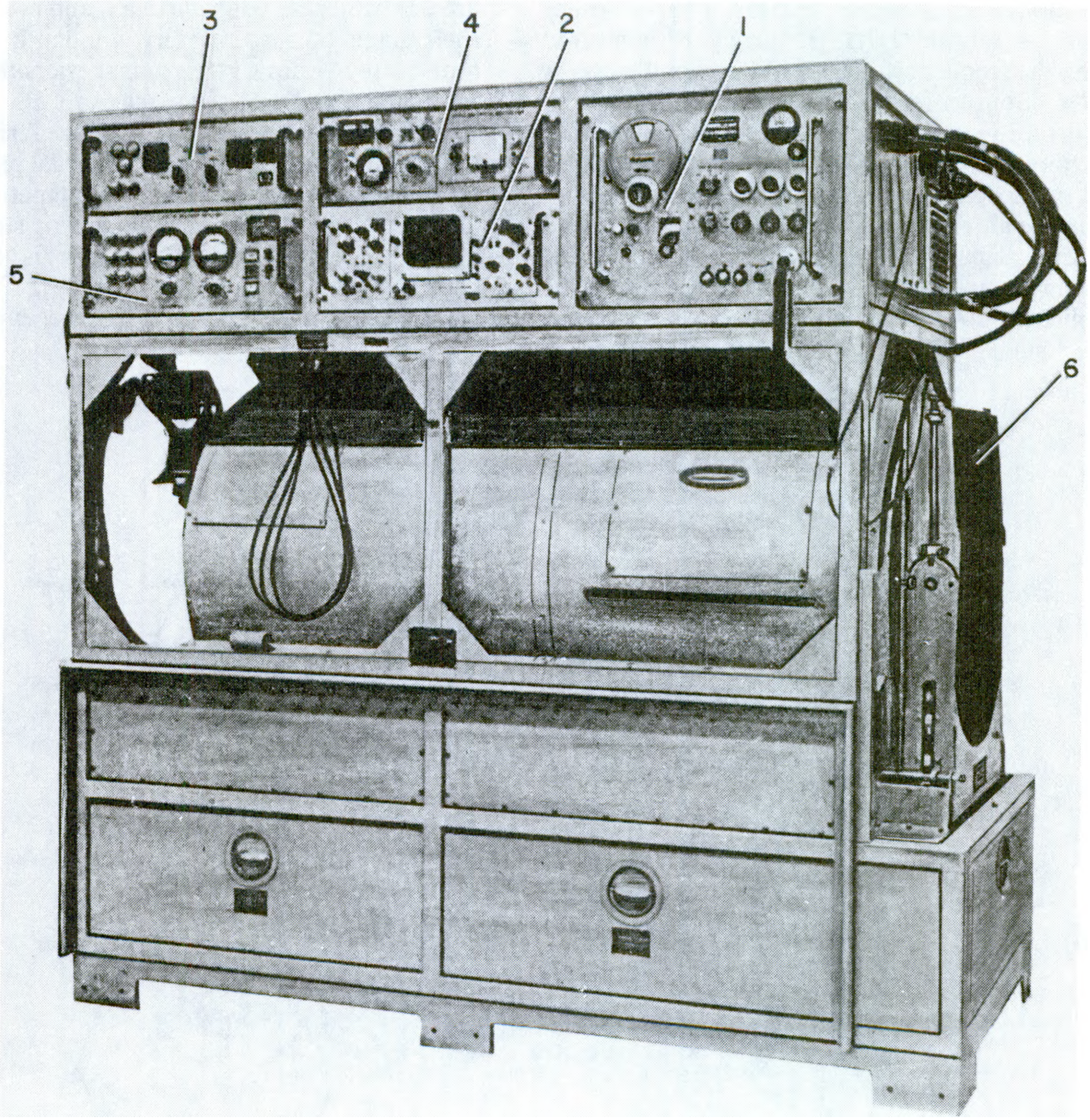
λ = wavelength

At this distance, the wavefront deviates no more than 1/16 of a wavelength from a plane wave front (the minimum deviation for accurate boresighting).

Antenna Boresight Test Set AN/APM-334

A test set that can simulate the electromagnetic far-field antenna test range is the AN/APM-334. The test set provides a means of converting the spherical wave fronts to plane wave fronts (fig. 1-24). The spherical wave fronts incident upon the lens are retarded in phase as they are propagated through the lens. This results in a plane wave front emerging from the face of the lens. The separation between the antenna receiver under test and the radiating source feed horn is reduced to approximately 4 feet.

The Test Set AN/APM-334 (fig. 1-25) is used for the radar system installed in the A-7



1. SHF signal generator
2. Oscilloscope
3. Servo control unit
4. Signal and crystal monitor unit
5. Control and power supply unit
6. Swing plate and utility lights section

223.38

Figure 1-25.—Antenna Boresight Test Set AN/APM-334.

aircraft. It is composed of an SHF signal generator (1), an oscilloscope (2), a servo control unit (3), a signal and crystal monitor unit (4), a control and power supply unit (5), and a swing plate and utility lights section (6).

Figure 1-26 shows an antenna mounted on the AN/APM-334 test set that is being boresighted. The SHF signal generator supplies the radar signal at the required frequency to the source feed horn for transmission through the lens to the antenna receiver. At the directional coupler, a portion of the radar signal is sampled. Its frequency is measured using the frequency meter and the signal monitor meter. Source feed-horn controls are used to position the source feed horn accurately within the boresight target area of the antenna receiver. The oscilloscope is used to visually monitor signals from the antenna under test. For a complete and accurate alignment or boresight procedure for any antenna, you should refer to the MIM for the applicable aircraft.

MICROWAVE FERRITES

Ferrites are usually powdered, compressed, sintered magnetic materials. They are unique because they have useful magnetic properties and are also insulators. RF fields can penetrate a ferrite while conducting magnetic substances cannot.

The more common ferromagnetic substances (iron, nickel, cobalt, and their alloys) are good electrical conductors. They cannot be used as magnetic materials at the higher frequencies because of eddy current losses. The ferrites are not subject to eddy currents, and even though their magnetic susceptibility is much lower than that of the ordinary ferromagnetic substances, they can be and are used extensively at the higher frequencies. It is possible to produce ferrites with a wide range of magnetic and electrical properties.

Garnets are another class of magnetic oxides. They are used extensively as magnetic substances at high frequencies. The garnet is a rather complex oxide (compared to ferrites). The garnet crystal can fit several of the rare earths into

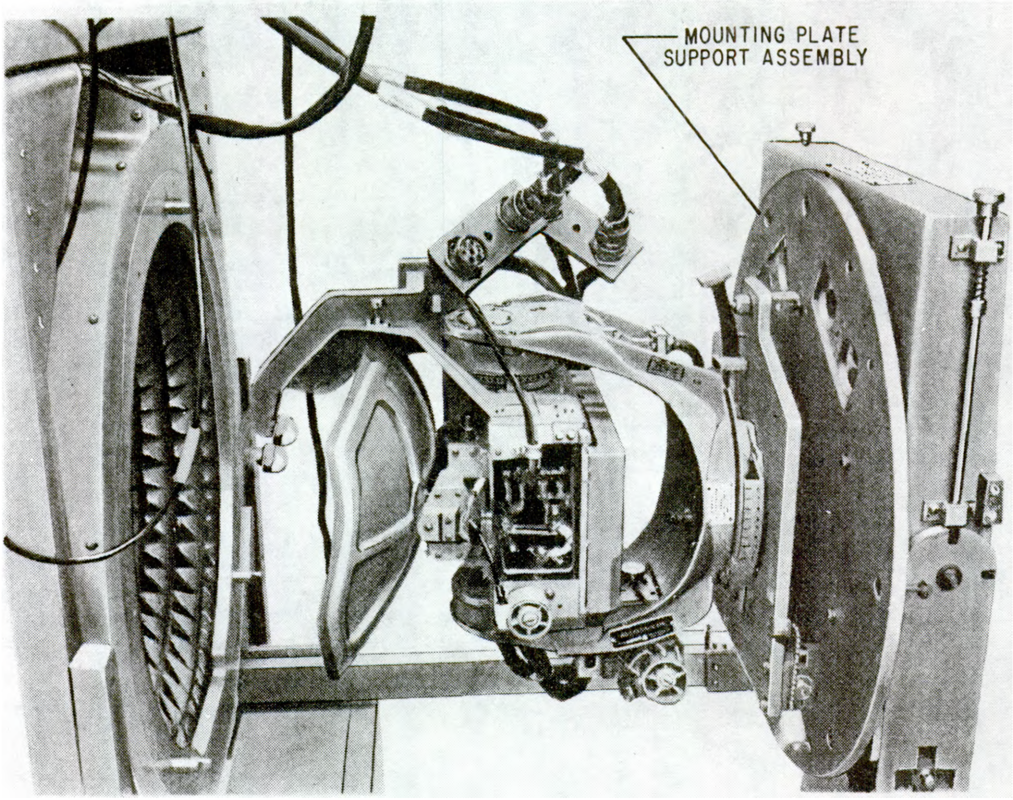


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Figure 1-26.—Antenna mounted on test set AN/APM-334.

its lattice. The rare earths have several unpaired inner electrons, therefore, they have strong magnetic properties. The yttrium-iron garnet is probably the most useful of the garnets at present. Certain devices employing ferrites could formerly be used only at microwave frequencies. The garnet has made it possible to use these devices at frequencies as low as UHF.

NONRECIPROCAL DEVICES

At microwave frequencies, the greatest use of ferrites is in nonreciprocal propagation devices. Nonreciprocal devices can be used to isolate a signal source from its load. A magnetron or other microwave signal source operating into a varying mismatched load (as in the case of a scanning antenna that is fed by a waveguide with rotating joints) tends toward frequency "pulling." If the reflected energy caused by mismatch is absorbed or diverted before it reaches the source, the source will see a constant load.

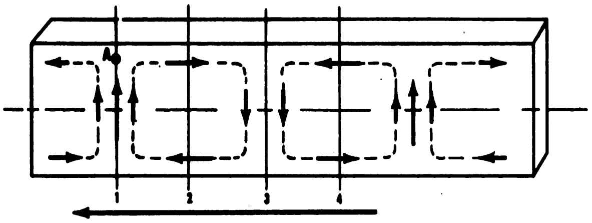

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Figure 1-27.—Rotating magnetic fields in a waveguide.

Ferromagnetic Resonance

Nonreciprocal ferrite devices make use of the interaction of the electron's spin with an external magnetic field. When a ferrite is placed in an external magnetic field, the atomic *magnets* within the ferrite tend to line up with the external field. For example, the electrons' spin axes line up with with the external field. A spinning electron has gyroscopic properties. When an external force attempts to change the spin axis, the electron precesses. Any gyro has a preferred or natural precession frequency that is proportional to the strength of the external field. By proper choice of ferrite and external field strength, the natural precession frequency can be made to occur at any selected microwave frequency.

An electromagnetic wave traveling down a waveguide produces, at a point off the centerline of the guide, a rotating magnetic field. This is shown in figure 1-27. As the wave advances from right to left, the stationary point A sees a clockwise rotating magnetic field as points 1, 2, 3, and 4 on the moving wave pattern go past. A wave traveling from left to right will produce, at point A, a magnetic field with counterclockwise rotation.

A slab of ferrite placed off-center in a waveguide (fig. 1-28) acts as a one-way device at a frequency which depends upon the external magnetic field strength. If the ferrite's preferred electron precession frequency matches

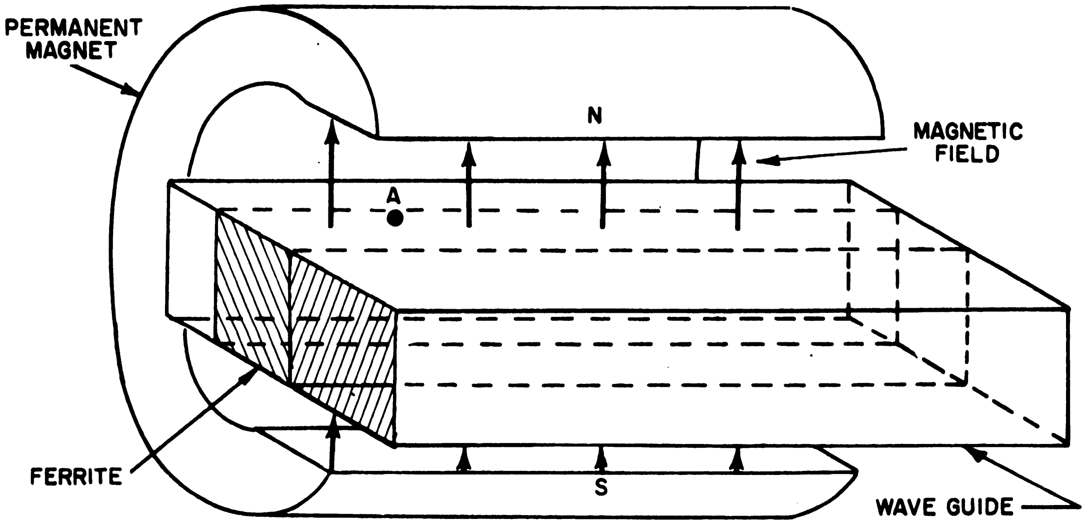

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Figure 1-28.—Resonance isolator.

the frequency of an RF wave traveling from left to right in the guide, the ferrite absorbs most of the energy in the wave. The rotating magnetic field as seen at point A aids the electron precession. The electrons precess vigorously and convert the RF energy to heat. This phenomenon is known as ferromagnetic resonance. A wave traveling from right to left is attenuated very little because its rotating magnetic field opposes electron precession. The one-way device shown in figure 1-28 is a resonance isolator.

Faraday Rotation

If a plane-polarized wave is propagated through a waveguide containing an axially

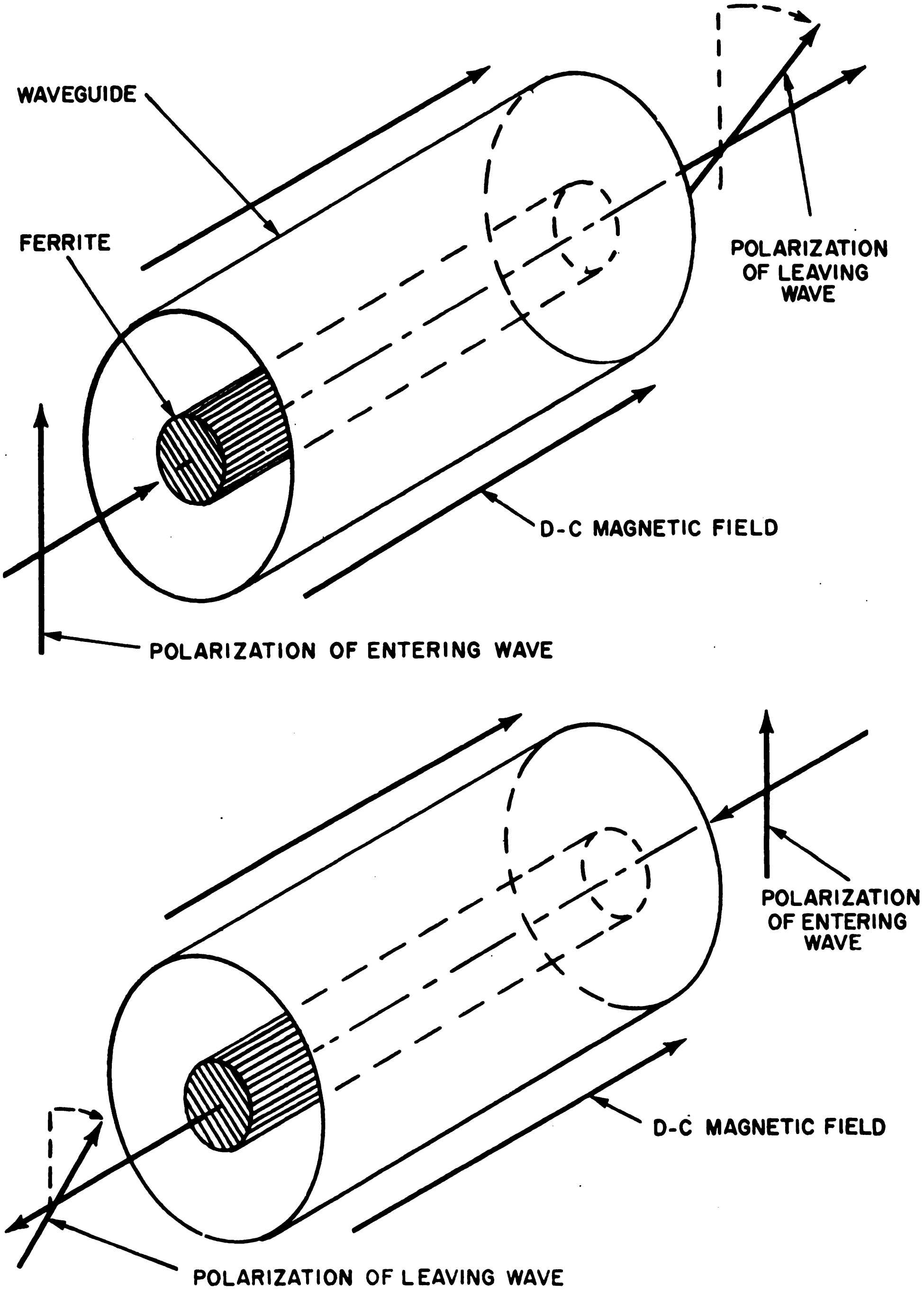
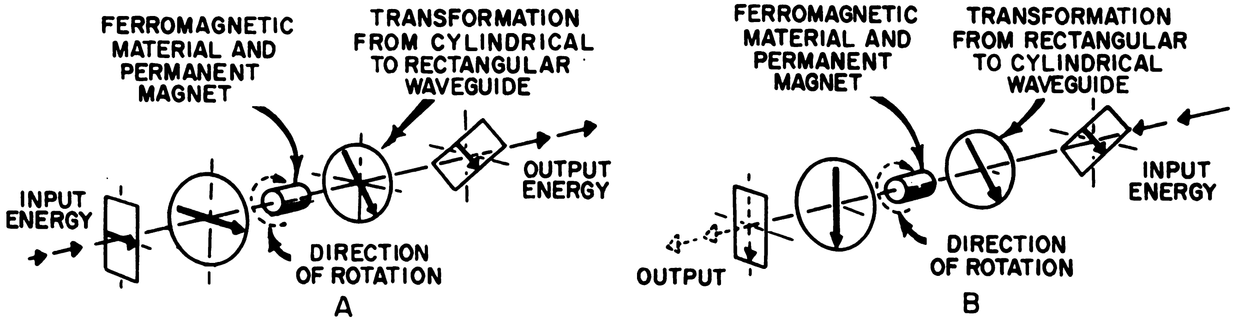

WAVEGUIDE
FERRITE
POLARIZATION OF LEAVING WAVE
D-C MAGNETIC FIELD
POLARIZATION OF ENTERING WAVE
POLARIZATION OF ENTERING WAVE
D-C MAGNETIC FIELD
POLARIZATION OF LEAVING WAVE
223.68

Figure 1-29.—Faraday rotation.

mounted ferrite rod, the plane of polarization rotates when a magnetic field is applied parallel to the direction of propagation. The amount of rotation depends upon the strength of the applied field and the dimensions of the ferrite rod. The sense or direction of rotation depends only upon the polarity of the magnetic field. Figure 1-29 shows Faraday rotation.

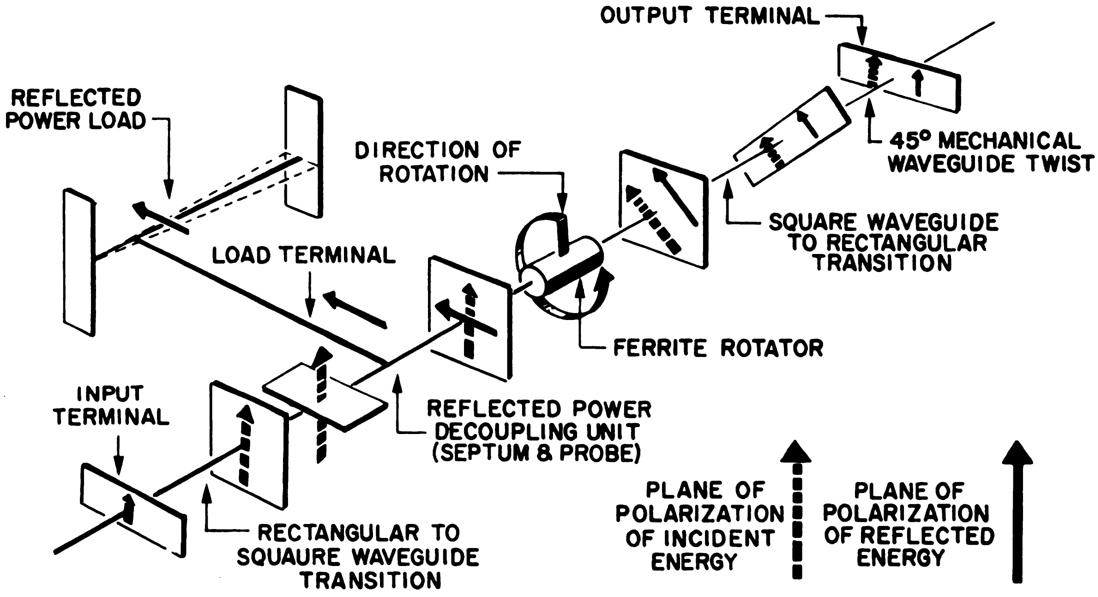
An isolator which uses the Faraday effect is shown in figure 1-30. A plane-polarized wave comes down the guide and goes through a rectangular-to-round waveguide transition. As the wave passes the ferrite, its plane of polarization is rotated 45 degrees clockwise, and it leaves through the rectangular guide (fig. 1-30, view A). If a wave comes down the guide in the reverse direction, it also rotates 45 degrees clockwise, and it leaves through the rectangular guide. If a wave comes down the guide in the reverse direction, it also rotates 45 degrees clockwise (as viewed on the left) as shown in figure 1-30, view B. The wave is 90 degrees from the transmission plane of the rectangular guide (the guide is cut off for this polarization) and the wave is reflected. Properly oriented vane type absorbers can absorb this energy without affecting waves traveling in the other direction.

In isolators designed to handle high power, the reflected wave can be coupled out to a separate power-absorbing load. An isolator of this type is shown in figure 1-31.


FERROMAGNETIC MATERIAL AND PERMANENT MAGNET
TRANSFORMATION FROM CYLINDRICAL TO RECTANGULAR WAVEGUIDE
INPUT ENERGY
OUTPUT ENERGY
DIRECTION OF ROTATION
A
FERROMAGNETIC MATERIAL AND PERMANENT MAGNET
TRANSFORMATION FROM RECTANGULAR TO CYLINDRICAL WAVEGUIDE
INPUT ENERGY
OUTPUT
DIRECTION OF ROTATION
B

223.69

Figure 1-30.—Faraday Isolator. (A) Wave traveling in the forward direction; (B) wave traveling in the reverse direction.

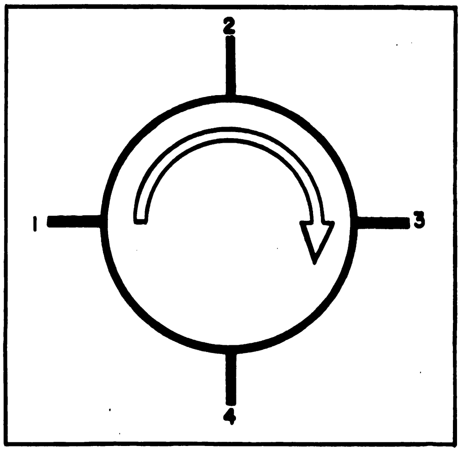

OUTPUT TERMINAL
REFLECTED POWER LOAD
DIRECTION OF ROTATION
45° MECHANICAL WAVEGUIDE TWIST
SQUARE WAVEGUIDE TO RECTANGULAR TRANSITION
LOAD TERMINAL
FERRITE ROTATOR
INPUT TERMINAL
REFLECTED POWER DECOUPLING UNIT (SEPTUM & PROBE)
RECTANGULAR TO SQUAURE WAVEGUIDE TRANSITION
PLANE OF POLARIZATION OF INCIDENT ENERGY
PLANE OF POLARIZATION OF REFLECTED ENERGY

223.70

Figure 1-31.—Faraday isolator with a separate load for absorbing reflected power.

Switches

A Faraday isolator can be modified to act as a single-pole, double-throw, waveguide switch. In the waveguide switch, the output end of the device has two rectangular output guides 90 degrees apart. Each output guide is 45 degrees from the input guide at the other end of the device. An electromagnet supplies the external field. Switching is done by reversing the direction of current flow in the electromagnet. Current in one direction causes the RF wave polarization to be rotated 45 degrees clockwise. Electromagnetic current in the opposite direction causes the wave polarization to rotate 45 degrees counterclockwise. In each case, only one of the output guides will accept the RF wave. Switching times of less than 1 μsec are possible. Isolation between the output guides (if they are properly terminated) is on the order of 40 dB. This type of switch can be used to switch a transmitter between two antennas.



223.71

Figure 1-32.—Four-port circulator.

Circulators

A circulator is a device that allows one-way propagation of signals through it. It may have several input-output ports. Figure 1-32 is a schematic of a four-port circulator. The arrow shows direction of power flow within the circulator. Power entering port one leaves by port two only; power entering port two leaves by port three only, and so on. This one-way power flow between ports results from rotation of the signal polarization between ports. Each port is so oriented that it cuts off for all signals except those that entered the port just before it. If it is properly terminated, each port accepts all of the power from the preceding port. Figure 1-33 shows

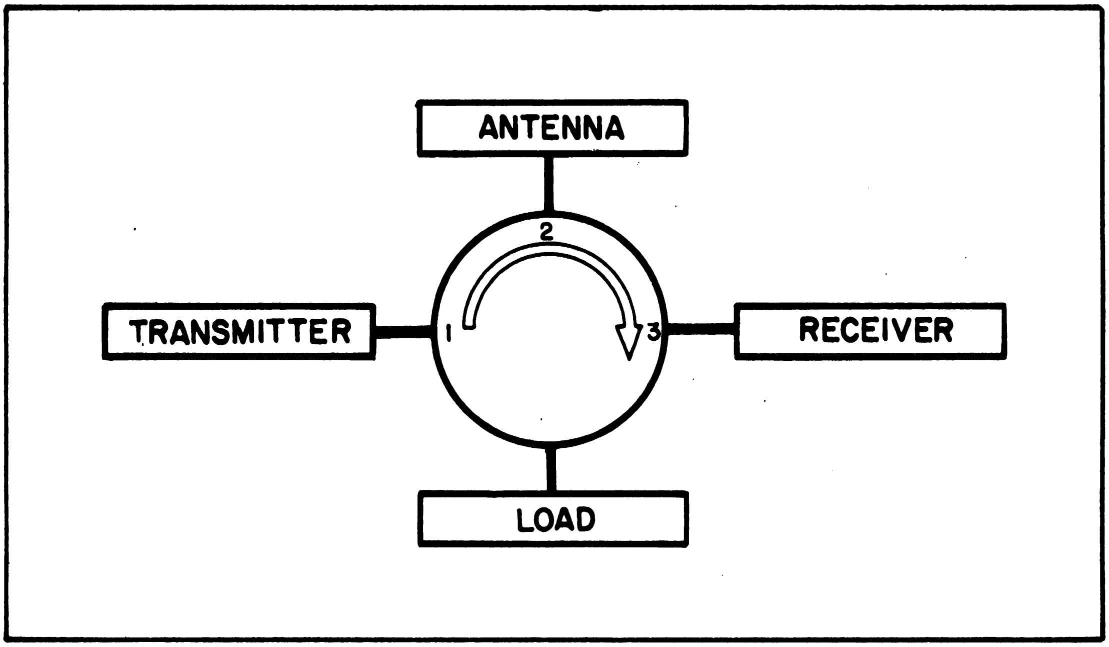


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Figure 1-33.—Four-port circulator used as a radar duplexer.

a four-port circulator used as a radar duplexer. The load at port four absorbs any local oscillator signal from the receiver and prevents it from being radiated.

RING DUPLEXER

The hybrid ring is a type of duplexer somewhat different from those already discussed. It is capable of performing the functions of the duplexer previously discussed. In addition, it is capable of handling high power with a minimum of impedance mismatch.

The ring duplexer is a coupling device which routes the RF energy from the magnetron to the antenna and the received signals (echoes) from the antenna to the receiver. It is a circular waveguide path to which connections are made at four critically spaced E-plane waveguide junctions. An E-plane (series) junction is one where branch arms join the waveguide at right angles across a wide side (A dimension) as shown in figure 1-34.

This type of junction is similar to a series connection to an open two-wire transmission line. Figure 1-35 shows the electric fields in successive wavefront positions for an analysis of an E-plane junction.

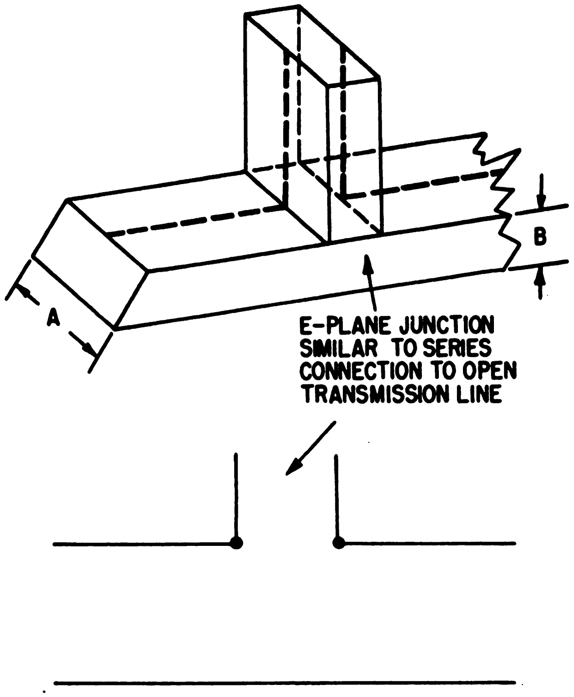
B
A
E-PLANE JUNCTION SIMILAR TO SERIES CONNECTION TO OPEN TRANSMISSION LINE

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Figure 1-34.—E-plane junction.

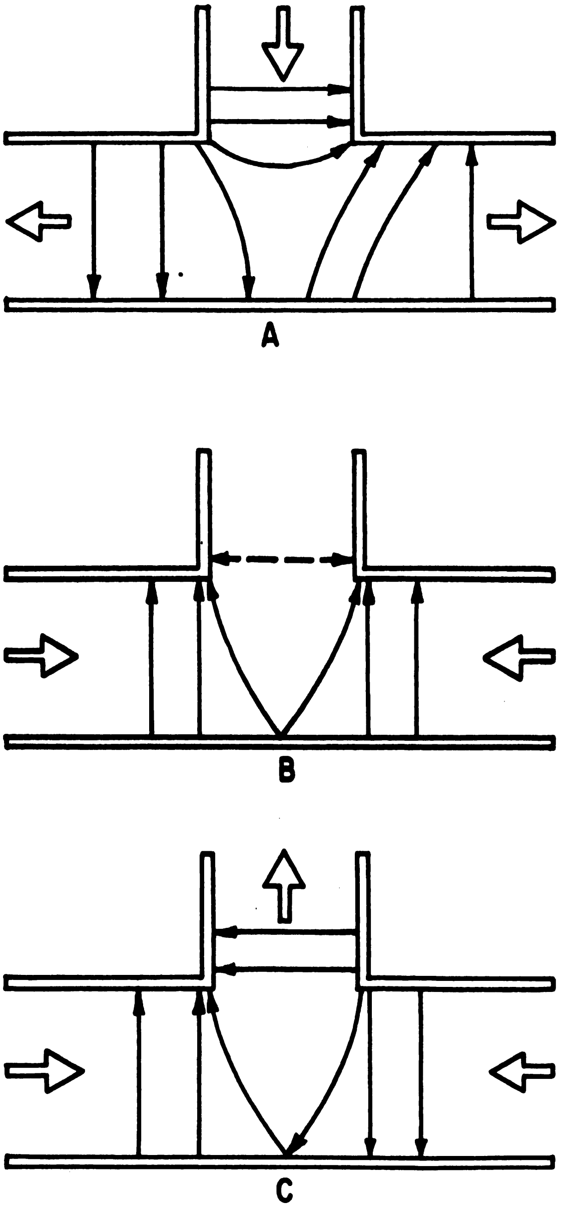

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Figure 1-35.—Electrical properties of waveguide junctions.

Signals arriving at the junction from the branch waveguide (fig. 1-35, view A) divide and are propagated down both of the in-line arms. The two signals leave the junction 180 degrees out of phase. In-phase signals arriving at the junction from the in-line arms (fig. 1-35, view B) combine in the branch waveguide 180 degrees out of phase and, if equal, cancel each other. Signals 180 degrees out of phase arriving at the junction from the in-line arms (fig. 1-35, view C) combine in the branch waveguide in phase and add.

The total length of the ring duplexer shown in figure 1-36 is 1 1/2 wavelengths. The branches are spaced 1/4 of a wavelength apart. The RF signal from the transmitting oscillator enters the hybrid ring duplexer and divides as illustrated in figure 1-36, view A. The two out-of-phase signals start in opposite directions around the ring. The signals enter the two arms of the duplexer leading the TR tubes V1 and V2. The TR tubes ionize, short-circuiting the paths as in the duplexer assemblies previously discussed. Most of the energy in the signals is reflected back toward the ring duplexer. The weak signals leaking past the TR tubes (shown by the light lines in figure 1-36, view A) travel equal distances and arrive at the magic T-junction 180 degrees out of phase. These signals enter the E-plane junction and are absorbed by the dissipative load. Transmitter energy does not enter the H-plane junction leading toward the signal mixer since out-of-phase signals cancel at this type of junction. The reflected energy from the TR tubes proceeds around the duplexer to the arm connected to the antenna. TR tube V1 is 1/4 wavelength farther from the ring duplexer than TR tube V2. Thus, the energy reflected from this tube travels 1/2 wavelength farther in the TR-tube arm. This signal travels 1/2 wavelength in the ring duplexer, while the signal reflected from V2 travels 1 wavelength in the duplexer. These signals

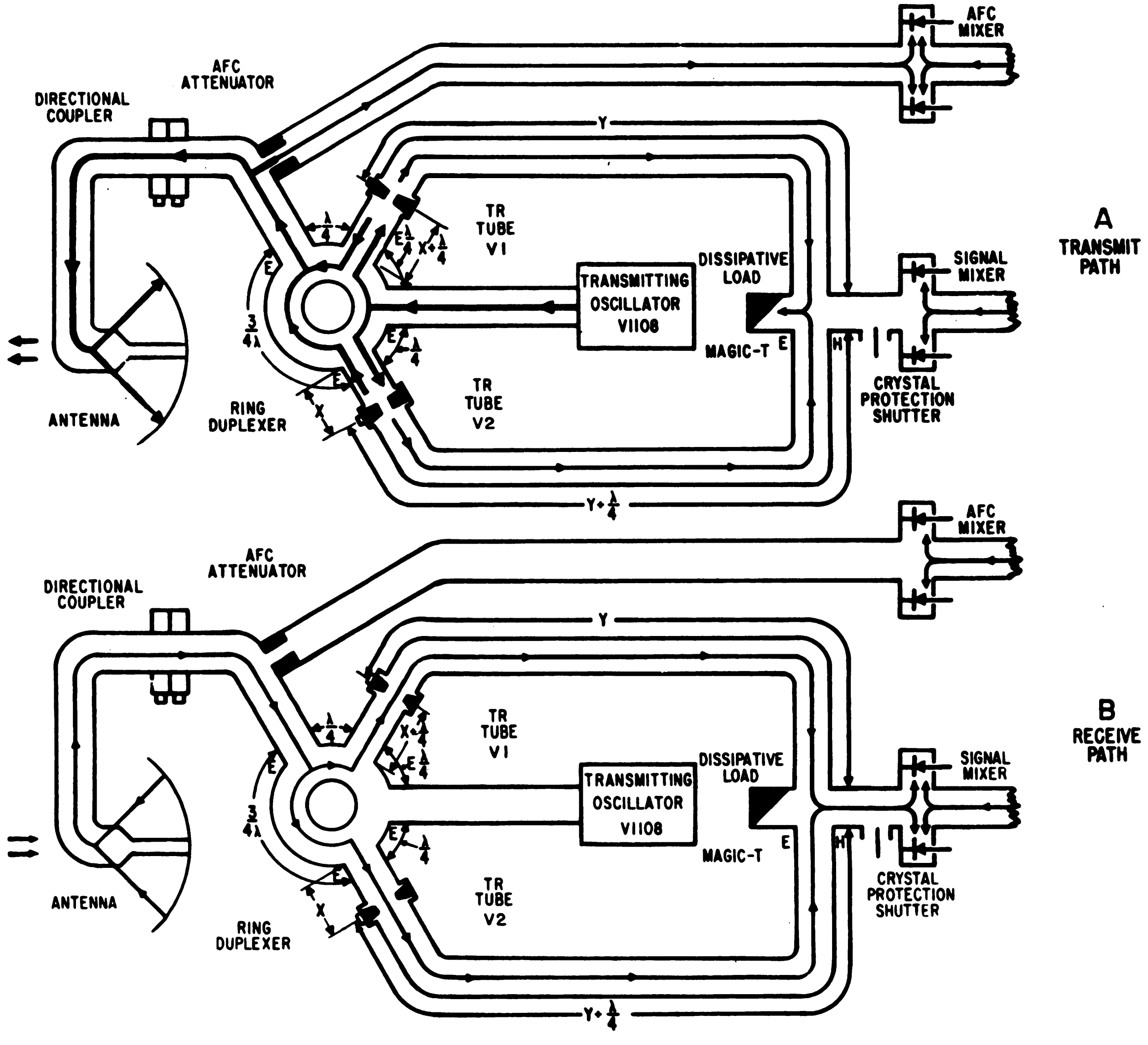

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Figure 1-36.—Ring duplexer.

have traveled equal distances when they reach the antenna junction and, since they left the magnetron arm out of phase, they arrive at the antenna junction out of phase. The antenna junction is also an E-plane junction. The two signals add and pass out through the transmitter arm. A greatly attenuated sample of the transmitted signal is taken from the antenna arm of the ring duplexer and conducted by waveguide to the automatic frequency control (AFC) mixer of the receiver section of the system.

The receive cycle of operation of a ring duplexer is shown in figure 1-36, view B. The received signals from the antenna leave the antenna arm of the hybrid ring 180 degrees out of phase. The distance traveled by the received signal reaching the magic-T junction through the arm of deionized TR tube V2 is 1/2 wavelength greater than that through the arm of V1. Therefore, received signals combining at the magic-T junction are in phase and enter the H-plane junction leading to the signal mixer.

When the power is off or when the system is in standby condition, a protective shutter is used to slide in the waveguide by relay action to protect the crystal mixers from radiation of nearby radar sets. The directional coupler (fig. 1-36) provides the same purposes as discussed on other duplexer systems.

Another advantage of the ring duplexer is that no ATR device is required. This advantage can be explained through the examination of the basic properties of hybrid junctions. Each of the side arms of the junction are terminated in the characteristic resistance of the arm. Then, the input impedance at the junction is equal to the terminating resistance. This allows for matching pairs of entries in such a manner that no power can be exchanged between entries of pairs. The ring duplexer is balanced in pairs so the arm from the antenna and the arm from the transmitter are matched. Also, the two arms containing the TR tubes are matched. When the input to the ring is from the antenna arm, as it is during receive time, the two voltage waveforms at the transmitter arm combine 80 degrees out of phase. Thus, the output voltage is zero so no power is delivered at the entry to the transmitter, and the power is divided equally between the loads at the arms containing the TR tubes.

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CHAPTER 2

SPECIAL COMPONENTS, CIRCUITS, AND SYSTEMS

A discussion of various types of special components, circuits, and systems which the AQ may be required to maintain is presented in this chapter. A knowledge of the construction and operating principles of special circuits can help when performing aviation fire control maintenance.

Upon completion of this chapter, you will be able to—

- Identify the advantages and components of pulse expansion and compression
- Recognize the applications and operating principles of pulse expansion and compression
- Recognize the applications and operating principles of continuous wave Doppler MTI
- Recognize the applications and operating principles of pulse-modulated Doppler MTI
- Recognize the applications and operating principles of coherent MTI
- Identify the advantages of using frequency-domain reflectometry (FDR) test sets
- Identify the operating principles of FDR test sets
- Identify the uses of the Swept Frequency Test Set (AN/USM-402(V))

TRAVELING WAVE TUBES

The evolution of radar has been partially the result of a continuing need to stay ahead of any new countermeasure tactics that may compromise the radar's effectiveness. The trend in search radars has been toward much higher power and toward electronic countermeasure (ECM) techniques that increase subjamming visibility. A good antijamming radar must be able to shift frequency quickly, and if possible, over a wide bandwidth to avoid the jammer's frequency. The trend in electronic warfare (EW) has also been toward wide bandwidth capability. In this case, the jammer amplifies wide bandwidth noise or deceptively retransmits the radar pulse to offset the radar's frequency shift tactics.

An amplifying device capable of broad operating ranges, with sufficient output power and efficiency, is necessary since wide frequency bandwidths are essential to the employment of such tactics. The traveling wave tube (TWT) offers promise in these areas.

The TWT is an electronic amplifying device which accepts a weak RF input signal and amplifies it many thousand times. It performs the same function as its principal predecessors—the triode, magnetron, and klystron. But, it has one characteristic not shared by these devices—an extremely wide bandwidth. The TWT exhibits relatively uniform characteristics within a 2:1 frequency range; i.e., within one octave. However, the TWT can provide useful gain well outside this range. For example, some TWTs will amplify all frequencies from 7,000 to 14,000 MHz while others will handle frequencies from 4,000 to 8,000 MHz, and so forth, without having to be tuned within their bandwidths. Normally, traveling wave tubes are not operated below 500 MHz or above 10,000 MHz.

Figure 2-1 shows a simplified helix-type TWT structure. At the left of the diagram is the

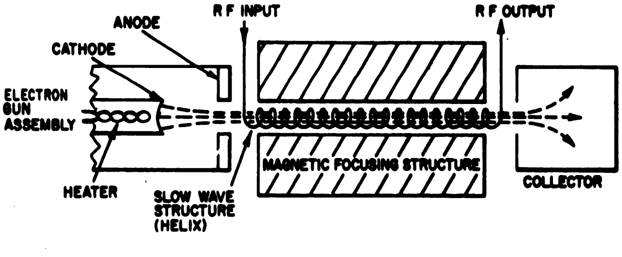

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Figure 2-1.—Simplified helix-type TWT structure.

electron gun assembly. When heated, the cathode emits a continuous stream of electrons. These electrons are drawn through the anode, focused into a tight, narrow beam, and forced to travel the length of the tube. Eventually, these electrons dissipate in the collector in the form of heat. At the same time the electron beam is moving through the tube, the desired RF signal is fed into a slow-wave structure consisting of, in this case, a tightly wound wire called a helix.

SLOW-WAVE STRUCTURE

The applied RF signal propagates around the turns of the helix at approximately the velocity of light. However, the axial RF electric field (because of the signal) advances toward the collector at a velocity considerably less than the velocity of light. The rate of advance of the RF wave is approximately equal to the velocity of light multiplied by the ratio of helix pitch to helix circumference. The helix is designed to slow down the wave propagation so that it can be synchronized with an electron stream that has a velocity corresponding to an accelerating voltage of approximately 1,500 volts.

The helix-type slow-wave structure is particularly suitable for achieving wide-band operation because the velocity of the axial field produced by the helix is almost completely independent of frequency over a wide frequency range. A typical helix-type traveling wave amplifier has a response which is constant to within ±3 dB from 2,000 to 4,000 MHz.

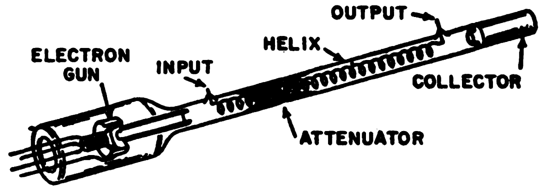
Many other types of slow-wave structures may be used in a traveling wave tube (such as a folded line or a periodically loaded waveguide). However, except for the helix, they are dispersive structures. They have a wave velocity that varies with frequency and so have less bandwidth than the helix. (Keep in mind that a TWT will amplify all frequencies for which the velocity of the wave is substantially the same as the velocity of the electron beam.) The helix-type traveling wave tube is a relatively low-power device. High-power traveling wave tubes nearly always have less bandwidth.

The phase velocity of the RF wave, or the speed at which the wave is moving forward, is made synchronous with the velocity of the electron beam. As a result, an interaction is created between the electron beam and the RF signal. The electrons in the beam are slowed by the RF field and move down through the helix in bunches. As the electrons are slowed, they give energy to the RF field. This results in great amplification of the RF signal by the time it reaches the output.

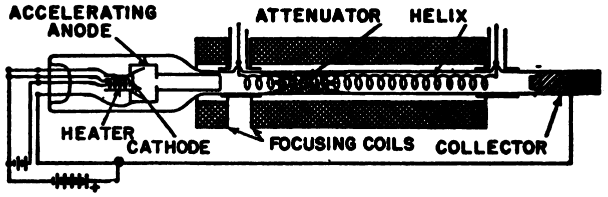
As shown in figure 2-2, a magnetic focusing field is provided to prevent the beam from spreading and to guide it through the center of the helix. A helix attenuator (commonly in the form of a conducting coating of Aquadag painted on the glass wall of the tube) is required to prevent the amplifier from going into oscillation as the result of backward waves and/or reflections that result from slight impedance mismatches at the terminals. The RF signal to be amplified is applied at the gun end of the helix and travels its length. The output power is removed at the collector end of the helix.

INTERACTION PROCESS

In order to understand the continuous interaction process, consider a constant traveling wave of RF electric field (fig. 2-3). The positive



(A) TRAVELING WAVE TUBE



(B) TUBE MOUNTED IN MAGNETIC FOCUSING DEVICE

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Figure 2-2.—Diagram of a typical traveling wave tube.

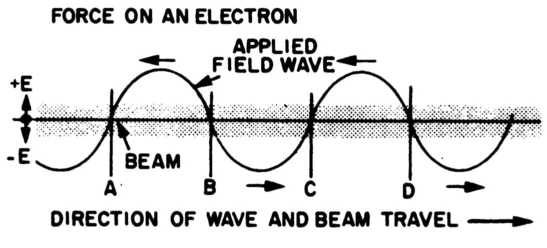

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Figure 2-3.—Beginning of the continuous interaction process.

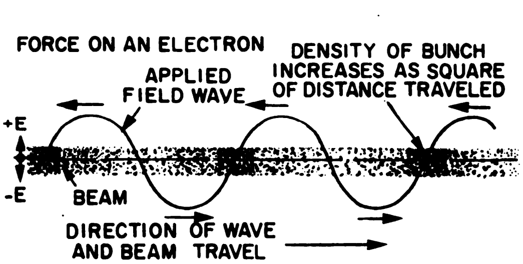
half-cycle of the RF electric field is tending to force the electrons to the left. During the negative half-cycle, the wave is tending to force electrons to the right. To begin with, a uniform distribution of electrons is traveling to the right at exactly the same velocity as the wave shown in figure 2-3.

Note that the electrons between C and D are falling back and accumulating at C. Also, the electrons between B and C are advancing and accumulating at C. In other words, a bunch is forming at C. Electrons in the half-periods on either side of B are moving away from B with the consequent formation of an antibunch at B. The bunch-formation process tends to be cumulative; that is, the longer the electrons are subjected to the field, the denser the bunch they form. The result of this process is shown in figure 2-4. If the traveling wave field remains constant, the charge density of the bunches grows as the square of the distance traveled until the charge density approaches a maximum.

As you observe the passage of the traveling wave and electron stream from a stationary position, note that the wave will appear as an ac (RF) voltage, and the bunches will appear as an alternating (RF) current. The amplitude of the alternating current (essentially charge density) is proportional to the square of the time electrons have been subjected to the field.

As these electron bunches move through the helix, they induce power on the helix and set up other traveling waves. The core of the helix may be considered to be divided into a series of gaps of minute lengths. The voltage across and the current through each gap is continually changing as the traveling wave and bunches pass by. The action of the beam may be analyzed on the basis of the action at each gap separately. Then, the total effect may be obtained by adding the actions at the separate gaps in proper phase. The induced power may be resolved into an induced field wave traveling to the right, as indicated in figure 2-5. For example, at gap 1, induced field waves (dE_1) are propagated to the left and right from z_1. Similar waves are initiated at all other values of z. The total field at any z is the sum of all induced waves arriving at the z from both directions.

Assume the electron velocity is equal to the traveling wave velocity. All field waves traveling to the right add exactly in phase and cause a secondary field wave to build up 90 degrees behind the original applied field wave (fig. 2-6). Waves traveling to the left do not add in phase. In fact, some of them add 180 degrees out-of-phase. So, a backward wave does not tend to build up. Refer to figure 2-5. When a bunch passes gap 1, backward wavelet dE_1 is initiated with a positive crest. Then 1/4 wavelength later, the same bunch initiates backward wavelet dE_2. By the time the positive crest of dE_2 returns to gap 1, dE_1 has passed through 180 degrees, is at a negative crest, and the two backward wavelets tend to cancel each other. Actually, dE_2 is greater than dE_1 since the bunch density is greater by


FORCE ON AN ELECTRON
APPLIED FIELD WAVE
DENSITY OF BUNCH INCREASES AS SQUARE OF DISTANCE TRAVELED
+E
-E
BEAM
DIRECTION OF WAVE AND BEAM TRAVEL

223.116

Figure 2-4.—Electron bunch density grows with square of distance covered.

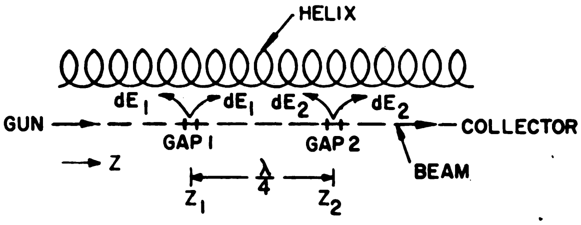


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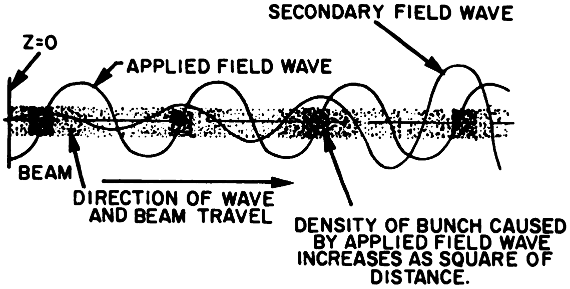
Figure 2-5.—Electron bunches induced opposite traveling field waves on the helix.


SECONDARY FIELD WAVE
Z=0
APPLIED FIELD WAVE
BEAM
DIRECTION OF WAVE AND BEAM TRAVEL
DENSITY OF BUNCH CAUSED BY APPLIED FIELD WAVE INCREASES AS SQUARE OF DISTANCE.

223.118

Figure 2-6.—The applied field wave induces an alternating current (bunching) on the beam which, in turn, induces a secondary field wave.

the time it arrives at gap 2. Therefore, a small total wave results that travels to the left. However, it is traveling at such a high velocity relative to the beam that it will cause no further interaction with the beam. The helix attenuator prevents this backward wave from returning to the input terminal where it could cause trouble.

Secondary Field Wave

As mentioned earlier, the charge density of the bunches begins increasing as the square of the distance traveled. This causes a secondary field wave to be induced in phase with the alternating current (bunch), and therefore 90 degrees out of phase with the original applied wave. However, the secondary field wave actually increases at a rate higher than does the current wave in the beam that induced it. The increase occurs because the bunches are actually inducing the infinitesimal waves which, in turn, add in phase to produce the secondary field wave. It can be proved mathematically that the secondary field wave increases as distance cubed.

The secondary field wave will, in turn, cause bunches to start forming 90 degrees behind the original bunches just like the applied field wave produced the original bunching. Since the secondary field wave is a growing wave, this new secondary bunching will increase as the fifth power of distance instead of as the square of the distance as caused by a constant-amplitude field. The secondary bunches then induce a new tertiary wave on the helix which grows as the sixth power of distance, and so forth.

Total Growing-Wave Concept

The final form of the growing wave traveling down the helix may be realized by adding the series of growing waves (secondary, tertiary, and so forth). You may arrive at a conclusion by the following reasoning: near the input, the strongest field is the applied field, and the field is relatively constant for some distance. The first increasing wave to have substantial amplitude will be the secondary wave (increasing as the cube of the distance). For some distance,. it will be the dominant wave and, the total wave will grow as the cube of distance. Next, the tertiary wave becomes dominant, so the total field appears to grow as the sixth power of distance, and so forth. Thus, the rate of growth is rapidly increasing as distance increases. As a result, the rate of growth is increasing as fast as the wave amplitude is growing: The growth is exponential.

Obviously, this total field wave is traveling more slowly than the beam and the original wave since it is composed of induced wave components, each of which lags the previously induced component by 90 degrees. Energy is actually being transferred from the beam to a composite wave traveling more slowly than the beam. This is mathematically true. Now you can see that the velocity of the electron beam does not have to be greater than the velocity of the applied traveling wave in order for the mathematical requirements for energy transfer to be satisfied. In fact, their velocities must be exactly synchronized to result in the most efficient operation.

Energy Transfer

Through analysis, the question of how the beam transfers energy to the traveling wave is answered. There is no net energy required to bunch the beam. On the average, as many electrons are sped up as are slowed down, and no energy is transferred from the helix to the beam in producing bunching. There is, however, a perfectly real energy transfer from the bunched beam to the helix. This induces a growing field on the helix.

In terms of the picture of the beam passing through a series of interconnecting gaps, the beam delivers power to each gap in the same way the bunched beam in a klystron delivers power to the catcher gap. Thus, at each stage of bunching, no energy is transferred; but, in setting up each field wave (secondary, tertiary, and so forth), the beam transmits energy to the helix.

ELECTRICAL CONSTRUCTION

All TWTs are constructed in the same basic manner. Some manufacturers vary the construction if a particular TWT is intended for a special purpose. The following paragraphs cover the largest number of TWTs presently in the Navy's inventory.

Electron Gun

The electron gun used in a TWT is like that of a projector lens. Its objective is to obtain as much electron current flowing in as small a region as possible without distortion or fuzzy edges. The design of the gun is extremely important since the gun is the source of electrons for the beam. A wide variety of guns have been developed in an effort to improve the gun optics to provide better beams.

Cathodes have been made of many different types of materials. Two types have become standard—the oxide type (having a nickel base with a barium/strontium coating) and the disperse cathode or the L-type (one version of which has an emitting surface consisting of porous tungsten through which barium atoms are dispensed from a chamber containing barium-strontium-oxide crystals). Two other types that are also used are the pressed-cathode and the impregnated types.

Recently, a number of tubes have been developed that have control grids. The use of a control grid makes it possible to turn the beam off and on rapidly with a much smaller voltage swing than is required when the cathode is modulated.

Helix Circuit

The helix circuit is considered to be the most efficient TWT circuit. It is capable of producing wider bandwidths than any of the more recently developed versions. However, its design is generally restricted to tubes having peak power outputs of less than 3,000 watts.

Single Helix

Figure 2-7 shows the principal component parts of a typical helix tube with its packaging and focusing structures removed. Helix coils are usually made of tungsten or molybdenum and are wound to extremely accurate dimensions. This accuracy is required because the fields associated with the slow waves must travel at the same axial speed as the stream of electrons emitted from the cathode. For example, in a 1,500-volt electron beam, the electrons travel at 1/13 the speed of light. Since the RF signal is carried along the wire from which the helix is wound at about the speed of light, the resulting linear ratio of the helix to the beam is approximately 13:1.

Helix-Derived Circuits

A number of configurations using the basic helix structure have been explored in an attempt to include higher output powers. An early attempt, the contrawound helix, uses two helixes wound in opposite directions. This device extends the useful range of operating voltages to the 20 to 70-kV range and allows the use of larger transverse dimensions at a given frequency range. The ring bar shown in figure 2-8 is a version of the contrawound helix.

Filter-Type Circuit

For some time, the TWT was considered usable only as a low-power device. At high powers, the basic helix structure has two major limitations: it has an inherent tendency to oscillate, and it is unable to dissipate the large volume of accumulated heat. Many other slow-wave structures have been investigated in an attempt to find a means of eliminating these

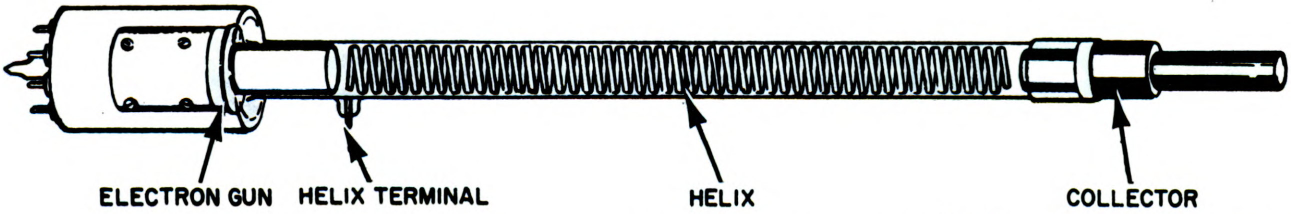


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Figure 2-7.—Principal parts of the helix-type traveling wave tube.

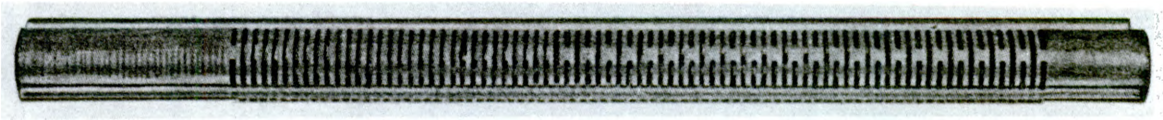

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Figure 2-8.—A contrawound helix.

undesirable limitations while retaining the TWT's wide bandwidth characteristics. Of the many types of circuits investigated, versions of the filter type have shown the greatest promise.

The simple waveguide is basically a high-pass filter. If a waveguide is periodically loaded, reflections will accumulate from the loading obstacles. The high-pass filter will become a band-pass filter with characteristics that depend upon the nature of the periodic loading.

Fundamental Forward-Wave Circuits

A number of circuits have been developed that use a perturbation of the basic waveguide mode, where the fundamental wave has its phase and group velocities in the same direction. One of these, the cloverleaf (named because the couplers resemble a four-leaf clover), has achieved up to 2 megawatts of peak power in the 1000 MHz to 6000 MHz range.

Spatial Harmonic Circuits

Another broad group of circuits uses a coaxial mode perturbed by the waveguide wall. The fundamental wave in these circuits has its phase and group velocities in opposite directions; therefore, a harmonic, usually the first, is used.

Note: These are all either backward-wave amplifiers or backward-wave oscillators. Spatial harmonics are also called Hartree harmonics and should not be confused with frequency harmonics. All spatial harmonics are of approximately the same frequency, but they are developed at different times as the electron bunch travels through the slow-wave structure; that is, they are related to their periodicity of the slow-wave structure.

The single slot, double slot, and drift tubes are examples of spatial harmonic circuits. Double-slot TWTs have been built that produce 1-MW peak output power over a 9-percent bandwidth, with gains also in the 20- to 30-dB region.

Coupled-Cavity Circuit

Recently basic waveguide mode resonators, coupled together by means of capacitive or inductive apertures to provide either a fundamental forward- or backward-wave circuit, have been

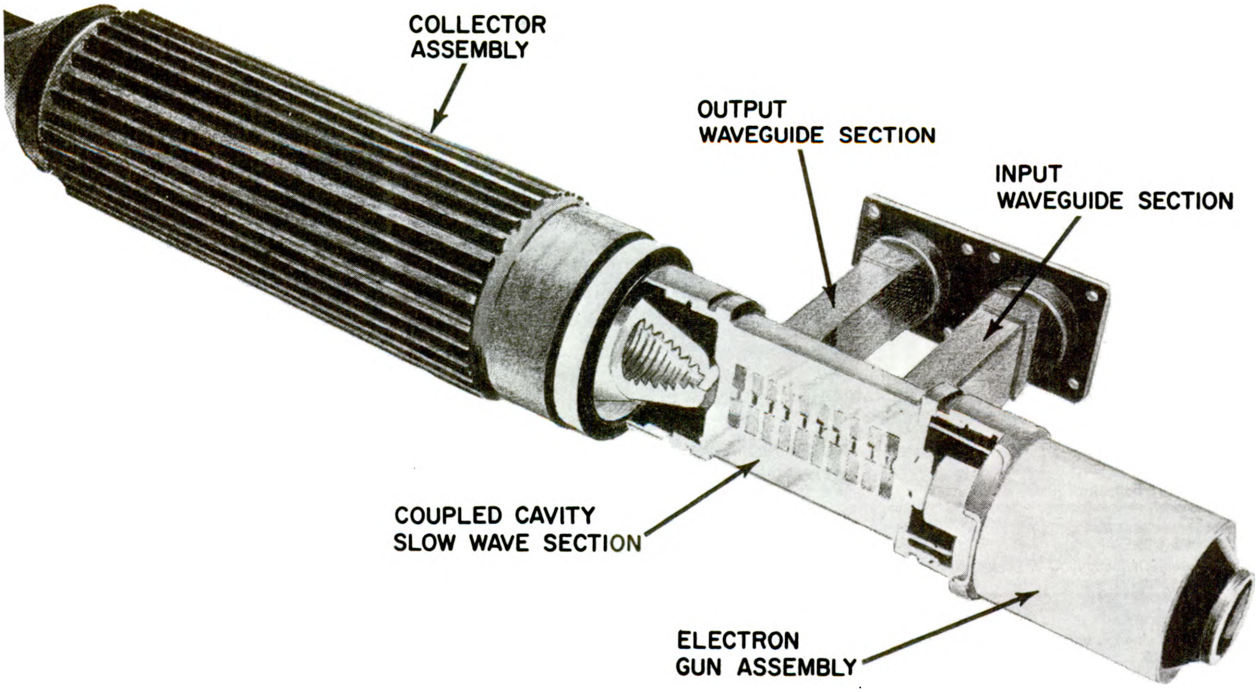

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Figure 2-9.—High-powered coupled-cavity traveling wave tube.

used. This device is known as the coupled-cavity circuit. Also it is known as a folded-waveguide circuit, since its structure resembles a waveguide folded in accordion fashion. Figure 2-9 shows a cross-sectional view of a high-powered, coupled-cavity tube of the spatial harmonic variety. The gun assembly is shown at the right end of the tube. The input waveguide is at the top right of the slow-wave structure. The output is to the left of the input. The cylindrical structure at the left end of the tube is the collector.

Originally, these structures provided frequency bandwidths of 10 to 15 percent. Recently, the bandwidth of these circuits has been increased by 40 percent and more. Tubes using this circuit have produced several hundred kilowatts of peak power from 1000 MHz up to 20,000 MHz, with up to 50 dB of gain.

The interdigital line is another version of the coupled-cavity circuit. It is used extensively in low- and medium-power amplifiers ranging in power output up to 1-kilowatt peak, with gains of about 30 dBs.

Helix Attenuator

The helix attenuator (fig. 2-2) was mentioned earlier in this chapter. It is important for you to note that the attenuator absorbs not only the undesired backward and reflected waves, but it also absorbs the desired forward applied field wave and growing wave on the helix. In other words, no traveling wave gets past the attenuator in either direction. However, the bunching of the electrons (accomplished by the applied wave prior to the attenuator) is unaffected by the attenuator. As the bunches of electrons emerge from the attenuating region, they induce the secondary field wave just as described here and as shown in figure 2-6. The helix attenuator does not alter the basic theory; but, if the attenuator had been included on the left side of figure 2-6, the applied field wave would not appear on the output side of the attenuator.

Focusing Structures

Since the beam tends to disperse or spread out as the result of the mutual repulsive forces between the electrons, some means is required for holding the electron beam together as it travels through the interaction structure of the tube. A magnetic field of the proper magnitude is used to confine the electron beam to the pencil-like cylindrical shape it must maintain. The three principal types of magnetic focusing discussed in this chapter are shown in figure 2-10.

SOLENOID FOCUSING.—The solenoid is still regarded as one of the best magnetic focusing structures. Its magnetic lines are parallel to the direction of travel of the electrons, it can be accurately aligned with the beam, and it provides excellent beam columniation. It will continue to be used in cases where the last bit of average power is required from a tube, and tube size and weight are not critical factors. To date, solenoids are used in most of the very high-powered TWTs.

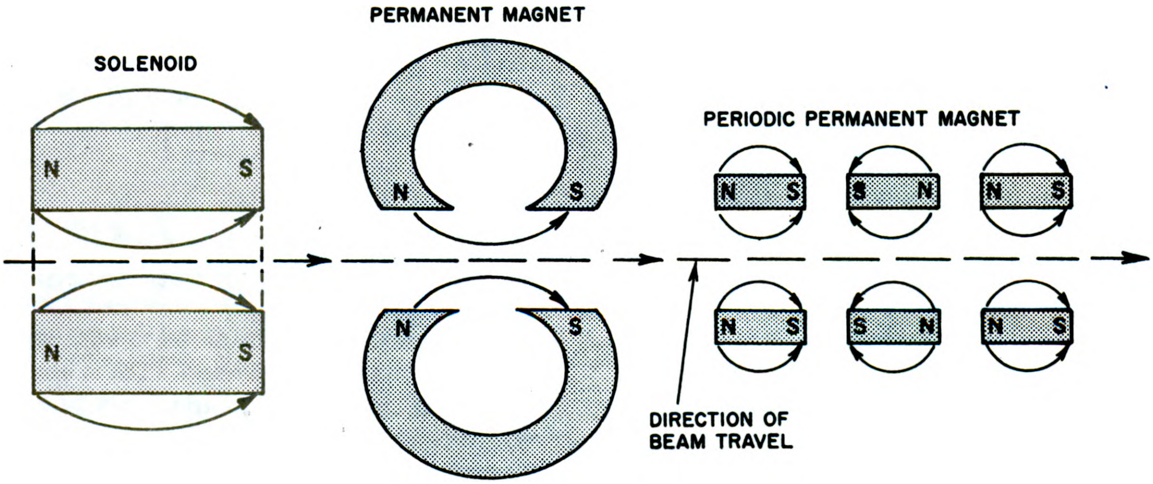

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Figure 2-10.—Three principal types of magnetic focusing.

Figure 2-11 shows a very high average powered TWT using a coupled-cavity interaction structure with solenoid focusing.

PERMANENT MAGNET FOCUSING.—In certain tube structures where the interaction structure is short enough, permanent magnet focusing is used instead of solenoid focusing. Figure 2-12 shows a coupled-cavity type TWT with its permanent magnet focusing structure.

PERIODIC PERMANENT MAGNET FOCUSING.—Perhaps the most important development in beam control has been the evolution of periodic permanent magnet (PPM) focusing, particularly its adaption to high-powered TWTs. Previously, its fundamental limitations were thought to restrict its use to low-powered TWTs where the beam power density is typically quite low. This light-weight focusing method fills a great need at the high-power levels where previous TWTs (with focusing solenoids) were too large and heavy for many airborne and space applications.

Figure 2-13 shows a cross-sectional view of a high-powered TWT, complete with focusing structure and external package. The tube is of the metal-ceramic, coupled-cavity type. Its total weight is 15 pounds. Its magnetic structure is composed of round disks represented in the cross section (fig. 2-13) by the black vertical areas at the extremities of the interaction structure. These magnets are separated by the lighter colored, iron pole pieces that function as magnet separators and form the interaction structure of the tube.

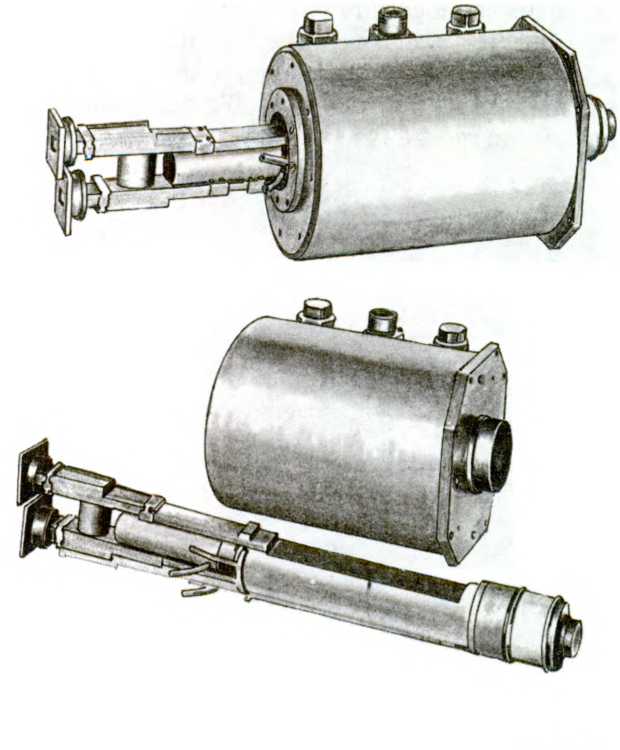

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Figure 2-11.—High-powered TWT using solenoid focusing.

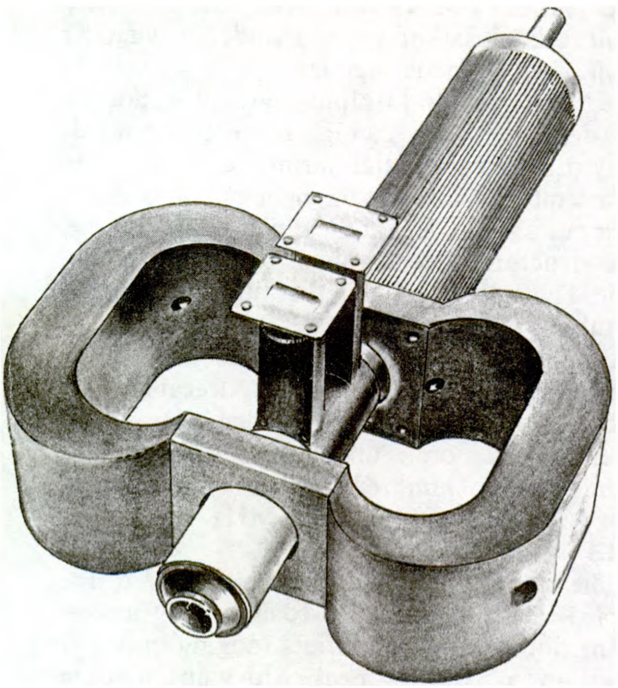

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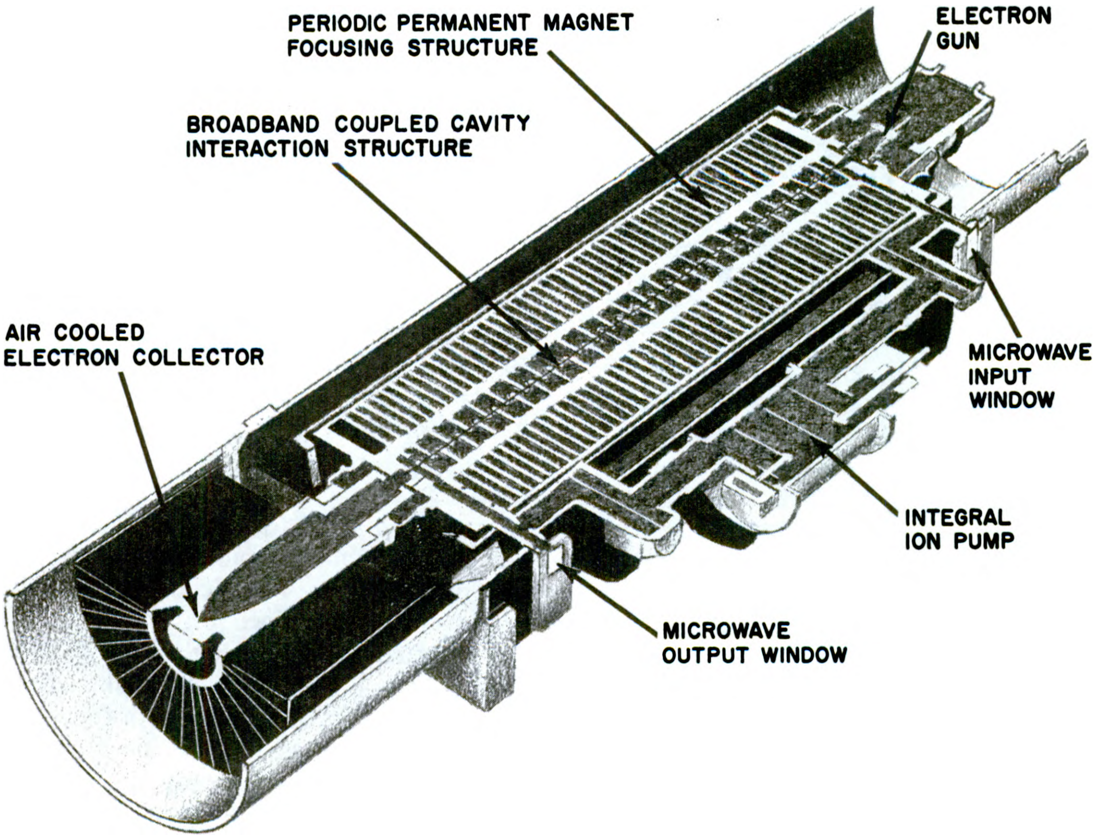
Figure 2-12.—High-powered TWT using permanent magnet.

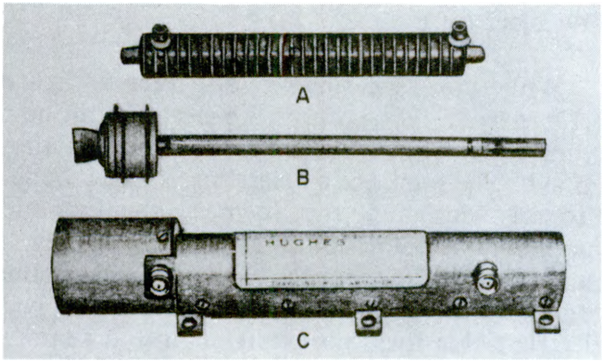
Figure 2-14 shows the use of PPM focusing in a helix-type, metal-ceramic TWT designed for space application. The PPM assembly is shown in view A. This structure is slid onto the helix tube (view B), properly aligned, and finally packaged as shown in view C. The tube provides 10 watts of CW power and has a total packaged weight of only 12 ounces.

ELECTROSTATIC FOCUSING.—Electrostatic focusing methods have been experimentally applied to low- and medium-powered TWTs with some success. Electrostatic focusing techniques require no magnetic field and, in principle, could provide even greater compactness and lighter weight than the PPM. However, the techniques currently available have not reached the practical stages where they can compete successfully with PPM focusing.


PERIODIC PERMANENT MAGNET FOCUSING STRUCTURE
ELECTRON GUN
BROADBAND COUPLED CAVITY INTERACTION STRUCTURE
AIR COOLED ELECTRON COLLECTOR
MICROWAVE INPUT WINDOW
INTEGRAL ION PUMP
MICROWAVE OUTPUT WINDOW

223.125

Figure 2-13.—High-powered TWT using periodic permanent magnet (PPM) focusing.



223.126

Figure 2-14.—Helix-type TWT using periodic permanent magnet (PPM) focusing.

Collector

The only function of the collector is to dissipate the electrons in the form of heat as they emerge from the slow-wave structure. This is usually done by conduction to a colder outside surface where the heat is absorbed by circulated air or liquid. The collector size is determined by the method of cooling used and the amount of energy that must be released.

MECHANICAL CONSTRUCTION

A disadvantage of the helix circuit has been the fragile glass vacuum envelope which encloses the tube parts. Actually, such glass structures are sufficiently well supported to withstand almost any environment and can tolerate very high shock and loads.

Recently, a means of using metal and ceramic materials in place of glass in helix tube construction has been developed. These tubes can withstand higher loads and can be vacuum fired at higher temperatures—typically 600° to 700° Celsius as opposed to 450° Celsius. This assures considerably better cleanup of undesired gases entrapped in the tube, which provides reliability at higher tube operating temperatures. Figure 2-14 shows a recent version of such a tube.

BACKWARD WAVE OSCILLATOR

The M-type backward wave oscillator (M-BWO) is a wideband, high-powered, highly efficient and reliable source of microwave power. It offers high speed, half-octave electronic tuning by variation of a single control voltage. Its most extensive application to date has been in ECM barrage and spot noise jamming.

During the early days of radar, the magnetron, with mechanical tuning, was the workhorse of microwave electronic warfare equipment. However, because wide and rapid tuning requirements are needed for both radar and electronic countermeasures, wideband electronic tuning of high-powered microwave oscillators is desirable.

The development of the voltage tunable magnetron and the principle of traveling wave interaction in linear beam tubes stimulated work on crossed-field traveling wave devices. This led to the development of the *carcinotron* and *M-BWO.*

The M-BWO has become an excellent microwave transmitter tube because it has the following characteristics:

- Voltage tuning
- High power and efficiency
- Versatility
- Economy of size and weight

BASIC PRINCIPLES

The M-BWO is a voltage tunable microwave power generator using the interaction of a ribbon beam traveling near a frequency-selective delay line. Electric and magnetic fields are maintained at right angles to each other and to the direction of the beam. The beam velocity is substantially the same as the phase velocity of a wave component traveling along the delay line. By this means, energy is transferred from the static field to the RF field. In the M-BWO, the RF energy travels in a direction opposite to that of the electron beam.

In most practical tubes, the interaction space is ring shaped. Figure 2-15, view A, shows a cross section of a typical tube. It also shows the path of the electron beam and the RF energy under oscillating conditions. Figure 2-15, view B, shows a three-dimensional cross-sectional view of an earlier M-BWO.

The M-BWO is a member of the traveling wave tube family described earlier in this chapter because it has the slow wave device, or delay line, and the bunching of electrons in the beam. The M-BWO differs from the TWT in several ways, including the use of the crossed magnetic field. You will probably recall that crossed magnetic fields are also used in the magnetron.

The principle of traveling wave interaction is basic to all crossed-field devices. The major objective of the device is to convert electrical energy from static (dc) form to electromagnetic energy in extremely rapid (microwave frequency) alternating form. The electron is used for this power conversion since it is able to link the two forms of energy. Reacting initially to the input or static conditions, the electron takes energy from the input and transports it to another part of the device. Here, the energy can be drawn upon to create an output or to amplify microwave signals.

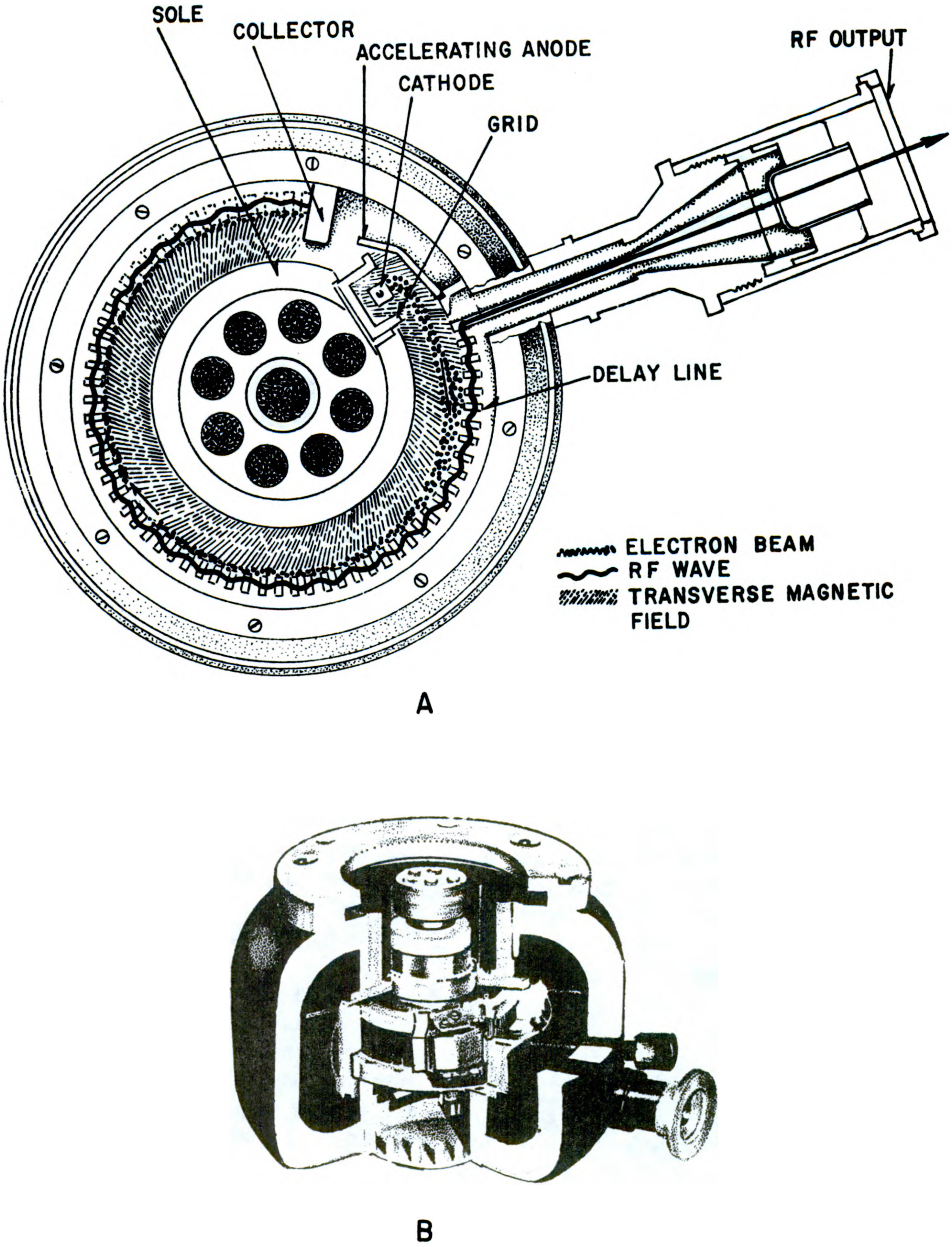
You have been introduced to two elements which require further explanation: the path of the electron from its source to its final destination and the *other part of the device* where the energy of the electron is finally used. Each element will be considered in turn; then, the combining of the two elements to form a working microwave tube will be discussed.

The Electron Path

While you read this section, refer to figure 2-15, view A. The path of the electron can best be understood by considering the forces acting upon it. The source of all electrons is the cathode. Properly designed and located, the cathode supplies a unidirectional stream of electrons. Immediately after the electrons are emitted, the combined action of magnetic and specially shaped electric fields form the electrons into a beam.

After the beam is formed, all of the component electrons travel at approximately the same velocity. The negatively charged electrons are injected into an electric field that is perpendicular to their forward motion. (This field arises from voltages applied between opposed elements—the anode and the sole. In the absence of other forces, a given electron would soon be *collected* by the positive element, the anode).

A second force acting upon the electron arises from its forward motion through a magnetic field



223.169

Figure 2-15.—Typical M-type backward-wave oscillator.

oriented crosswise to both the electron path and the previously described electric field; hence, the term *crossed-field* tube. By the conventional rule for this situation, the resultant force on the electrons is opposite to the force of the electric field. Appropriate adjustment of the fields results in a controlled beam path that is circular and terminates at an element called a collector. To summarize: The electron beam is formed at the electron gun (cathode), follows a circular path between the anode and the sole, and terminates at the collector.

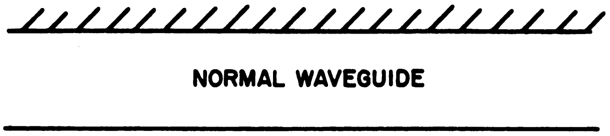
When the forces acting on the beam are expressed in standard electrical terms and equated for the controlled beam condition, the electrical force equals the magnetic force. Therefore, electron or beam velocity is equal to the ratio of electric field strength (E) to magnetic field strength (B). For the practical situation, B is constant and is supplied by a permanent magnet integral with the tube. Thus, beam velocity is directly related to E, the field strength between sole and anode. In more practical terms, E is given by the potential difference between the anode and the sole, then divided by the distance between them (which is fixed). Therefore, beam velocity is linearly controlled by variation of either the anode voltage or the sole voltage.

The Delay Line (Anode)

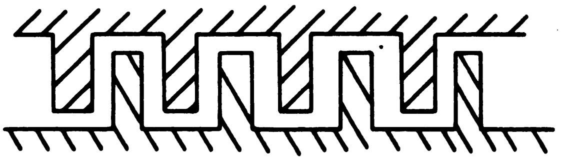
The next step in understanding the basic principles of the crossed-field device is to consider the part of the device where the electron beam develops microwave energy.

The sole serves as little more than one of the electrodes for the static electric field, as previously discussed. The anode is a much more complex component than has been suggested. In many crossed-field tubes, the anode is of such a form that it is called an *interdigital delay line.*

The interdigital delay line is best described as a normal waveguide transmission medium in which opposing walls have been extended toward one another in alternately spaced fingers or digits (fig. 2-16). The velocity wave travel in the resulting interdigital structure is decreased because of the longer path along its boundaries. In effect, such a structure develops a series of space harmonics whose summation is seen as microwave energy propagated at the delayed or reduced rate.



NORMAL WAVEGUIDE



INTERDIGITAL DELAY LINE

223.170

Figure 2-16.—Interdigital delay line compared with a normal waveguide.

One type of magnetron, called the ***interdigital magnetron***, uses an interdigital transmission line as the interaction space in the generation of RF power. The action of that device is more or less a combination of the conventional magnetron and the backward wave oscillator.

Interaction

As the electron beam travels in a circular path between the sole and the anode (delay line), electrons of the beam pass near the fringe fields of the noise-generated space harmonic waves on the delay line. For electrons of a given velocity, as determined by the externally applied delay line voltage, space harmonics of synchronous phase velocity result. Whether these are forward or backward waves is determined by the design of the delay line. In either case, since phase velocity of space harmonic waves is, in general, a function of frequency, it is the velocity of the electrons that determines the operating frequency.

The total field in this case is a combination of the externally applied fields and the internally developed space harmonic field. By following the laws governing electron motion in crossed electric and magnetic fields, electrons drift in a direction perpendicular to the space harmonic fields. This drift is such that they congregate in bunches, one bunch per space harmonic wavelength.

In the bunches, electrons work their way across from the original beam position to the slow wave structure (delay line), staying locked in synchronism as they do so. Their direction of motion is such that they give up to the RF field the energy acquired from the dc source, thus causing the space harmonic wave to grow.

PHYSICAL AND ELECTRICAL CHARACTERISTICS

The basic elements of the M-BWO, together with the usual polarities of applied dc voltages, are shown in figure 2-17. The arrangement of the basic elements can be separated into three regions.

1. The gun region, including the cathode, grid, and accelerator
2. The interaction space, including the delay line and the sole
3. The collector element and the sole

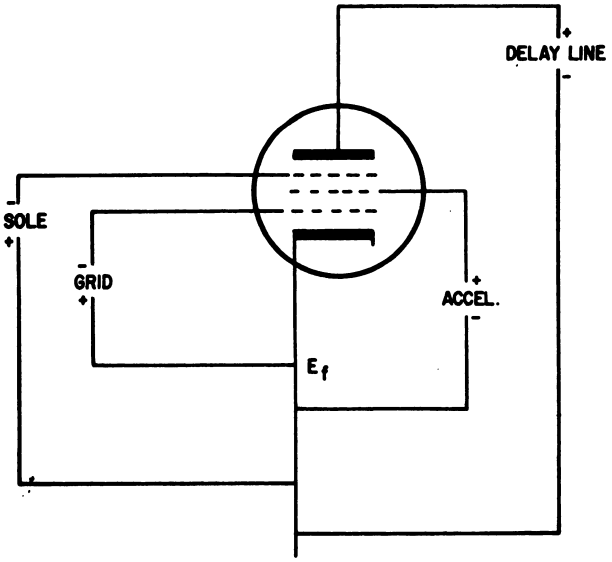


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Figure 2-17.—Schematic equivalent of an M-BWO.

A particular delay line can be designed for either forward wave or backward wave propagation. The distinction between the two arises from comparison of the direction of the dominant space harmonic with the direction of the energy that sustains it.

The amount of delay is established by adjusting various dimensions within the line. As with the more familiar waveguide, the delay line is a broadband device capable of transmission over a considerable frequency range. Its physical shape is a matter of convenience and, in this case, it is circular (shown in fig. 2-15).

Production of the space harmonics is the same as in any oscillator, starting with noise and leading to generation of usable frequencies. These frequencies are determined by the fields of the device in a manner similar to the action of a magnetron.

In brief, the electrons serve as a link between the externally applied input energy and the microwave output energy. By their velocity, the electrons determine the output frequency in an oscillator (and the optimum frequency for an amplifier). At the same time, they determine by their quantity (beam current magnitude) the power output level.

In contrast with magnetrons, the use of a beam in crossed-field tubes eliminates cathode back bombardment. This increases emission life. In contrast with linear beam devices such as a traveling wave tube, where beam velocity and tube frequency are functions of the square root of the tuning voltage, BWOs provide a very nearly linear relationship between tuning voltage and tube frequency.

In practical tubes, the collector and the delay line are integral parts of the tube body and are maintained at ground potential. The beam miser is an exception. It places the collector at cathode potential. The components of the electron gun include a heater, cathode, control grid, and accelerator anode. The control grid is operated at zero potential or slightly negative with respect to the cathode. The accelerator electrode is maintained at a positive potential with respect to the cathode. The sole electrode is negative with respect to the cathode, and the delay line (commonly referred to as an anode) is positive with respect to the cathode. With appropriate values of applied potentials and the appropriate value and direction of magnetic field, the electron beam is formed in the gun regions. This beam passes through the interaction region and is collected at both the delay line and the collector.

In backward wave oscillators, there is no RF input. A portion of the delay line adjacent to the collector is modified to assure absorption of any power reflected from the output.

The principal projections from the main tube body are the RF output connector and the *header*, through which the electrode leads are brought out to external terminals. A doughnut-shaped magnet is used, since this form combines high internal magnetic field strength with excellent external magnetic self-shielding properties.

FREQUENCY TUNING AND MODULATION

The oscillator can be tuned through the designed range of frequencies by varying the delay line-to-cathode or sole-to-cathode potential. This can be done statically or dynamically at rates limited chiefly by modulating power and interelectrode capacitances.

The average rate of tuning for a given tube design is nearly linear throughout the range, and all tubes are very similar. In present tubes of different frequency ranges, the sensitivity differs from approximately 0.13 MHz per volt at X-band frequencies to approximately 1.0 MHz per volt at K-band frequencies. The sole potential can be varied for frequency modulation with the advantage of requiring less modulating power. Since frequency is determined by the anode-to-sole potential, both sole and anode (delay line) tuning sensitivities are essentially the same. Sole modulation is limited to 1/2 of the complete tuning range of the tube, due to tube electronic characteristics.

Amplitude Modulation

Amplitude modulation is performed by varying the accelerator potential, since this electrode controls delay line current. The amplitude modulation is accompanied by an inherent frequency modulation that results from frequency pushing. (Frequency pushing is defined as an RF frequency variation due to a variation in anode current.) Pushing is not linear over either the frequency range or the current range. Amplitude modulation linearity is good, but it may be limited at low modulation frequencies by cathode fatigue during high current peaks. The grid electrode should not be used for amplitude modulation purposes. A dc potential on the grid may be required for optimum tube efficiency.

Pulse Modulation

BWO tubes are designed primarily for CW operation. However, it is possible to pulse the accelerator electrode and obtain peak power output considerably in excess of the CW power. Some delay line current is present even at zero accelerator potential. Therefore, in some cases it may be desirable to bias the accelerator negatively to obtain complete cutoff and pulse positively from the level of cutoff bias.

INSULATION AND COOLING

Normal heat dissipation, principally at the delay line and collector, usually requires that external liquid cooling be provided to this region. A coolant channel that is an integral part of the delay line serves this purpose. The coolant is provided through external connections. The coolant generally used is Dow Corning 200 silicone oil. This oil is thermally stable with a high resistance to changes in temperature. For high altitude operation, the input bushing can be pressurized or immersed in an insulating liquid.

In some applications, the tube is operated with the cathode at ground potential. When this method of operation is used, primary to secondary high voltage insulation of the various supply transformers is unnecessary. However, high voltage isolation of the RF output connector is necessary and additional safety precautions are required.

SPECIAL CONSIDERATIONS

Most microwave tubes have characteristics that limit their use or that require special consideration in their use. The following is a list of factors you should remember when using the tubes in a system.

- Voltage tuning sensitivity at X-band frequencies is approximately 1 MHz per volt. Thus, for a CW signal, the power supply must be well regulated with a low ripple factor. Although the average tuning sensitivity is nearly linear over the frequency range, there are variations in sensitivity for small frequency changes.

- The sole current changes in magnitude with frequency tuning, and it can be in either direction.

- Frequency pushing results from variations of other tube parameters. This may or may not be significant.

- Interelectrode leakage current of a small value exists in tubes of present design.

- A small amount of frequency pulling is a characteristic of the M-BWO. Therefore, these tubes are somewhat susceptible to load voltage standing-wave-ratio (VSWR) variations. Generally, load isolators are not required when load VSWRs are equal to or less than 1.5 to 1.

- After full beam current has been established, stabilized frequency will be reached in 2 minutes or less.

- Interelectrode capacitances must be considered as modulating frequencies are increased.

- Power output varies over the tuning range primarily due to the necessary change in input power when tuning. Therefore, a 3-dB power variation may be encountered over the tuning range.

THE BEAM MISER

The beam miser is a unique type of depressed collector that is used in beam-type, crossed-field traveling wave tubes. It allows a significant increase in efficiency and power with no additional external connections or other changes in tube or circuit. The depressed collector operates at a lower voltage than the anode or delay line, rather than at the same voltage.

The beam miser consists of a collector internally connected to the cathode and consequently at cathode potential. Thus, the anode current is reduced for a given beam current, or the beam current is increased for a given anode current. By analogy, the beam miser has some of the advantages of a reentrant electron beam in crossed-field tubes. A considerable part of the spent beam is unused. This part can be returned to the cathode instead of being wasted by normal collection at anode potential.

The use of a beam miser in standard M-BWO permits power increases of about 30 percent for normal operating anode currents. It has also permitted suitable operation of one tube at several power levels; that is, it has multiple operating current capability. A tube with a beam miser requires no external mechanical changes or additional electrical input connectors. Therefore, it is directly replaceable in the same socket as a standard tube not having a beam miser.

PARAMETRIC AMPLIFIERS

The parametric amplifier (also known as a reactance amplifier) is a device capable of low-noise amplification. The low-noise amplification of these devices offers phenomenal radar range improvements on existing equipments with minimum cost and maximum economy.

The parametric amplifier increases the power level of a signal by means of the variation of an energy-storage parameter. An everyday example is that of a child on a swing. The oscillation is maintained by "pumping"; that is, the child lowers his/her center of gravity on the downswing and raises it on the upswing. For maximum oscillation, the pumping takes place at twice the frequency of oscillation.

PRINCIPLES OF OPERATION

The principle of operation of one form of parametric amplifier can be shown by an LC circuit oscillating at its resonant frequency (fig. 2-18). Assume that the plates of the capacitor can be physically separated and returned to the original position. If the capacitor plates are pulled apart as shown at point B and the voltage is at maximum across the plates, then work has been expended on the capacitor since a force had to be applied to separate the plates. This work appears as an increase in voltage across the capacitor since

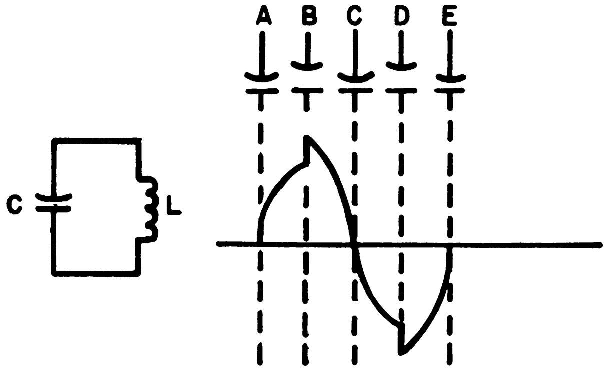

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Figure 2-18.—Capacitor plates varied by a pump.

$$E = \frac{q}{C}$$

and the charge q remains constant while capacitance decreases. Capacitance is inversely proportional to the thickness of the dielectric:

$$C = \frac{kA}{t}$$

Energy has been added to the system by the source that separated the capacitor plates. This energy transfer is referred to as pumping, and the energy source is referred to as a pump.

If the plates of the capacitor are returned to their original separation (fig. 2-18, point C) when the voltage is zero (zero charge on the plates), then no work is done and the voltage is unchanged. As the voltage passes through the maximum negative at point D, the plates are separated and voltage increases again. The frequency of the pumping source is twice the resonant frequency of the tank circuit.

Several devices may be used in parametric amplifiers to vary the capacitance or inductance electronically. The device most frequently used as a variable capacitor for microwave frequencies is the varactor diode (variable-capacitance diode). The capacitance of the varactor diode may be varied by changing the reverse bias on the diode. A discussion of varactor diodes is presented in

Chapter 12 of *Aviation Fire Control Technician 3 & 2, Part 2,* NAVEDTRA 10387-D.

Degenerate Mode

The simplest parametric amplifier requires the pump frequency to be exactly twice the resonant frequency of the tuned circuit or signal frequency. This mode of operation is known as the degenerate mode. Figure 2-19, view A, shows a basic parametric amplifier in the degenerate mode.

The degenerate parametric amplifier requires low pump frequency and power to operate. Also,

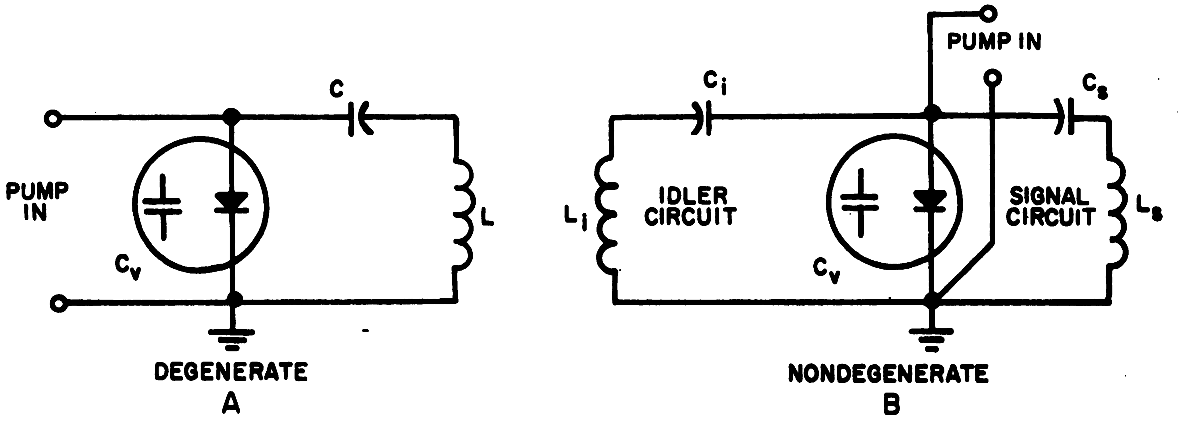

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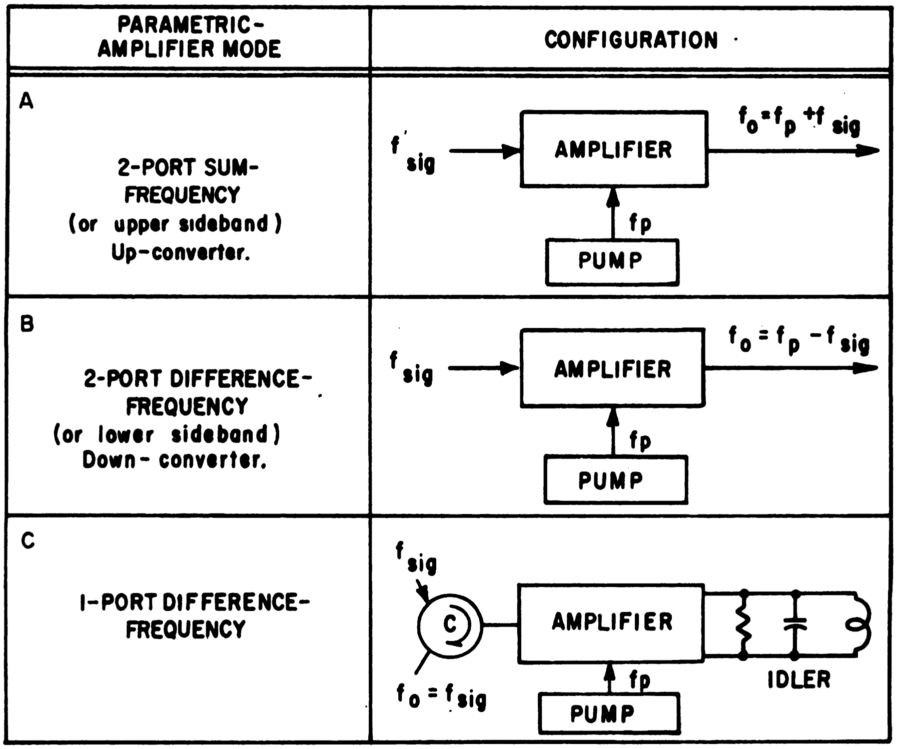
Figure 2-19.—Basic parametric amplifiers.


PARAMETRIC-AMPLIFIER MODE
CONFIGURATION
A
2-PORT SUM-FREQUENCY (or upper sideband) Up-converter.
f_{sig}
AMPLIFIER
$f_o = f_p + f_{sig}$
fp
PUMP
B
2-PORT DIFFERENCE-FREQUENCY (or lower sideband) Down-converter.
f_{sig}
AMPLIFIER
$f_o = f_p - f_{sig}$
fp
PUMP
C
1-PORT DIFFERENCE-FREQUENCY
f_{sig}
C
AMPLIFIER
$f_o = f_{sig}$
fp
PUMP
IDLER

223.174

Figure 2-20.—Basic configuration of the parametric amplifier.

it is the least complex to design. Because it is frequency and phase sensitive, the degenerate amplifier cannot be used in most radar sets.

Nondegenerate Mode

In a practical case, the separation of the signal frequency and the pump frequency cannot be conveniently maintained constant; but it will drift in and out of the optimum condition periodically, resulting in modulation of the signal frequency. Thus, the output may contain the pump frequency (f_p), signal frequency (f_s), and the pump frequency plus or minus the signal frequency. When the output contains the pump frequency plus or minus the signal frequency, it is called the idler or image signal (f_i). A parametric amplifier which includes an idler circuit is called a nondegenerate amplifier (fig. 2-19, view B). If the output frequency is higher than the input frequency, the amplifier is referred to as an up-converter. If the output frequency is lower than the input frequency, the amplifier is called a down-converter.

Figure 2-20 shows three basic configurations of the nondegenerate parametric amplifier that are used most often. In the two-port sum-frequency arrangement (shown in fig. 2-20, view A), the overall noise figure is higher than in other modes of operation, and the amplifier has only moderate gain. The pump frequency is less than the signal frequency. This is important since available pump power decreases with frequency. Thus, this amplifier is most useful at the highest frequencies. The name *two-port* comes from the fact that the output terminals are different from the input terminals. In the two-port difference-frequency mode of operation (fig. 2-20, view B), the amplifier has a relatively narrow bandwidth, high gain, and a low-noise figure.

In the one-port difference-frequency mode (fig. 2-20, view C), the parametric amplifier has the lowest noise figure. It is also fail-safe because the system would continue to operate with near the same noise figure if the pump were to fail. However, a circulator must be used to separate the amplified output from the incoming signal. This also aids in maintaining amplifier stability because it is sensitive to source impedance changes.

The operation of the one-port difference-frequency parametric amplifier (fig. 2-21) for the achievement of low-noise amplification is discussed in this paragraph. The varactor D (variable-capacitance diode) must couple together all the resonant sections at three frequencies—signal, idler, and pump. For amplification to occur, the sum of the idler and signal frequencies must equal the frequency of the pump. The signal frequency must be much lower than the idler frequency to achieve low noise. However, due to the imperfect nature of the varactor, there is an upper limit for the idler frequency at which noise increases. The capacitance of the varactor

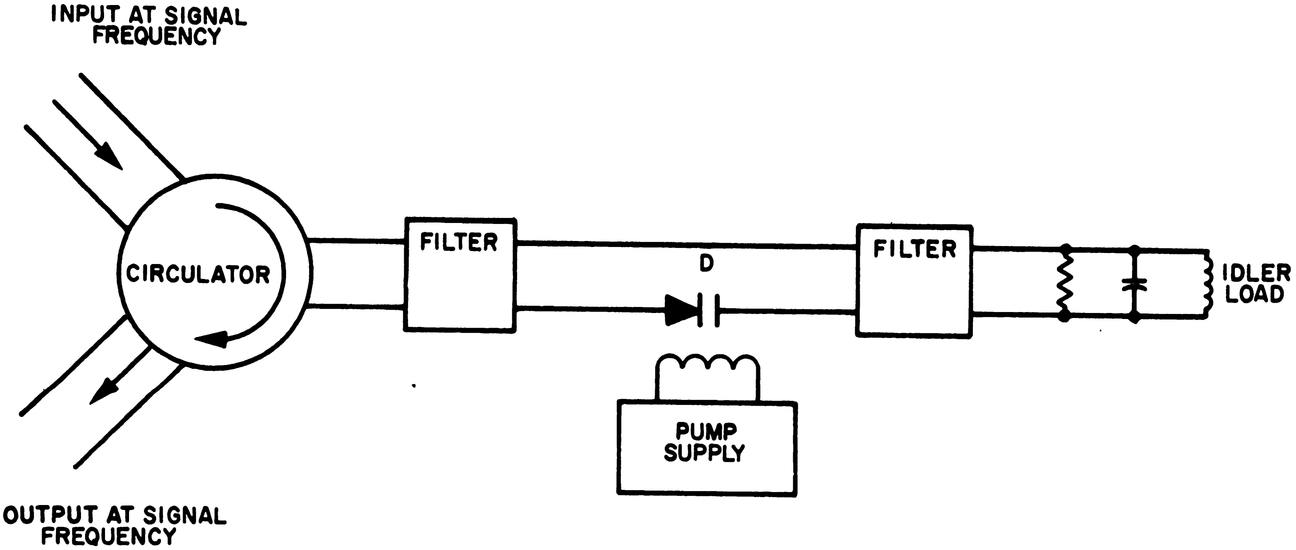


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Figure 2-21.—One-port difference-frequency parametric amplifier.

varies at the pump frequency rate by power from the pump. Some of this power is transferred and added to the signal when the two frequencies are mixed resulting in power amplification. The output signal is then taken from the circulator, which separates the input and output signals.

TRAVELING-WAVE PARAMETRIC AMPLIFIER

The tuned circuits used in the parametric amplifiers discussed in the previous section are usually of the coaxial- or cavity-type resonator. These amplifiers have a narrow bandwidth (less than 5 percent of the center frequency) because of the high Q resonators. By using a traveling-wave structure and sacrificing some gain, parametric amplifiers can be designed to provide bandwidths as high as 60 percent of the center frequency. Figure 2-22 shows a traveling wave parametric amplifier.

The traveling wave amplifier consists of a multistage low-pass filter. This filter is composed of a transmission line or lumped inductances and pumped shunt varactor diodes. The filter is terminated at the desired output frequency, and this signal is not reflected to the input. The signal and pump frequencies are injected at one end of the traveling-wave structure and the desired output taken at the opposite end. The signal, pump, and idler frequencies are within the bandpass of the filter, and the sum of the pump and signal frequencies are outside the bandpass. As the wave travels down the line, the idler and signal voltages increase as energy is transferred from the pump. Although gain increases as the length of the traveling-wave structure is increased, the resistive losses also increase. There is an optimum length of line for maximum gain. The main disadvantage of the traveling wave parametric amplifier is that it has a lower gain than the narrow-band amplifier.

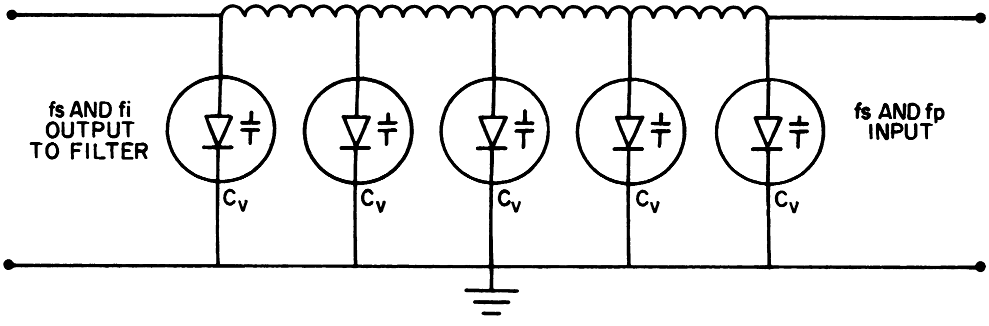

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Figure 2-22.—Traveling-wave parametric amplifier.

DIRECT VIEW STORAGE TUBE

A direct view storage tube (DVST) is similar in many respects to a conventional CRT. The DVST does have some differences that make it superior for an airborne radar display. Its chief advantages are as follows:

- Higher light output when required
- Longer persistence of the display highlights
- Persistence controllable for adaption to a wide variety of conditions such as search/track
- Possibly, a smaller overall package design

Other advantages could be mentioned; but discussion is limited to these.

Figure 2-23 shows a DVST. The entire tube is potted within its magnetic shield to provide protection against mechanical shock, vibration, humidity, and leakage between bulb terminals.

The major difference between CRT and DVST display devices is the inclusion in the DVST of a low-velocity electron gun (known as the viewing or flood gun). It is the viewing gun that offers the advantages of the DVST. The viewing gun electrons provide all of the significant light output from the DVST and, since it is the major difference between the DVST and the CRT, a discussion of the viewing gun and its operation will answer many questions you might have on storage devices of this type.

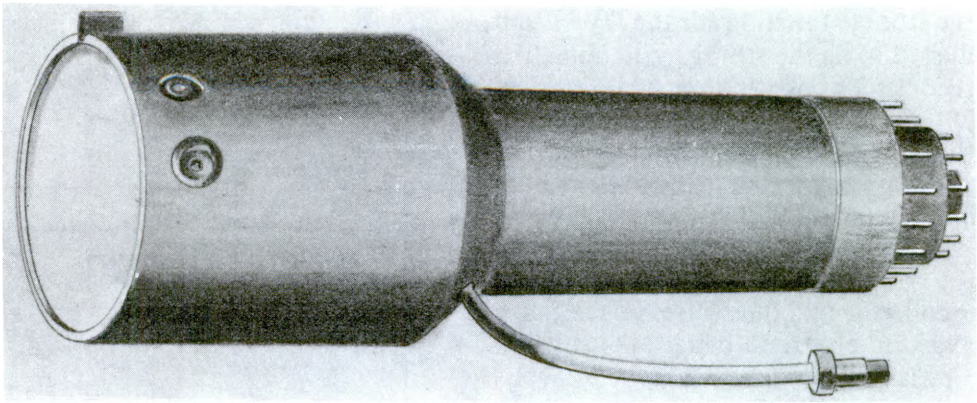

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Figure 2-23.—Direct view storage tube.

While reading this section, you should make constant reference to figure 2-24. The heater/cathode combination performs the usual function of emitting electrons, and the screen provides the conversion of electron energy to light energy, its usual function. The other parts and functions are discussed below.

Grid No. 1. Viewing grid No. 1 is unusual because its major function is NOT signal insertion or the cutting off of electron flow. The negative field between it and the cathode serves only to shape the electron beam.

A2. This grid, sometimes known as grid No. 2, also affects the shape of this electron beam and accelerates the beam toward the screen. However, since this element is common to the *writing gun*, it also affects the focus (astigmatism) of the writing gun. Therefore, it has a very limited operating range unless the mean potential of the writing gun deflection plates is made adjustable.

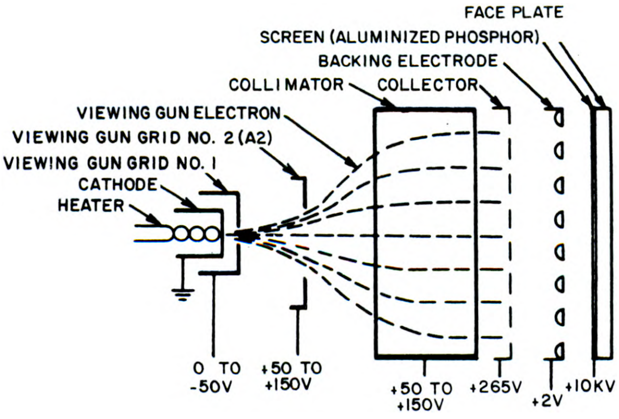

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Figure 2-24.—DVST pictorial diagram.

Collimator. This electrode is in the form of a large cylinder that the diverging electron stream must pass through on its way to the screen. The stream is made to diverge (spread out) by adjustment of the grid No. 1 and A2 voltages. In this case, this is the meaning of shaping the electron stream. In theory, the collimator now attempts to influence this diverging electron stream so as to make parallel or collimate these diverging electrons. As can be seen from figure 2-24, this element can be made positive or negative with respect to A2. Therefore, it can create a positive or negative field to accomplish collimation. In actual practice, it is more important to achieve uniform current density than a parallel beam. This is done by observing the screen for as nearly a uniform illumination as possible while adjusting A2, grid No. 1, and the collimator voltages.

Collector. The collector is an electrode that consists of a tightly stretched fine wire mesh. It provides additional acceleration of the collimated beam. Because the collector is a mesh, about half of these electrons will pass through. The remainder will be collected directly by the collector. It has the additional function of collecting secondary electrons emitted by the backing electrode.

Backing electrode. The backing electrode performs the storage function for the DVST and is often referred to as the storage grid. Like the collector, it consists of tightly stretched, fine wire mesh. Additionally, the back of this mesh is coated with a material that has the property of emitting, on the average, more than one secondary electron for each primary high velocity electron that strikes it. By looking at figure 2-24, you can see that the viewing gun electrons that pass through the collector find themselves in a negative field, the backing electrode being at +2 volts. Since their initial velocity is low (only +265 volts from cathode to collector for acceleration), they approach this backing electrode at almost zero velocity. Under the initial conditions shown in figure 2-24, most of the electrons drift through the mesh and are rapidly accelerated by the screen voltage, which can be as high as +10,000 volts.

The viewing gun electrons are now high velocity electrons. When they strike the phosphor, they illuminate the entire screen area (or nearly so if the tube has been previously collimated). If the backing electrode is made negative with respect to the viewing gun cathode, fewer electrons pass through it, and there is less light emitted from the screen. If this process were to be carried far enough, complete cutoff of light would be accomplished since all electrons approaching this negative electrode would be turned back to the collector. This can be done by a process called erasing.

A usual value for backing electrode cutoff is about −6 volts. Because of this, any time the side of the backing electrode facing the cathode is between −6 volts and 0, the screen has some degree of illumination (maximum at 0, minimum at −6 volts). The backing electrode can be considered as a capacitor, with the mesh as one plate and the backing materials as the other.

NOTE: The backing material is a poor conductor or semi-insulator and therefore insulates itself from the mesh while acting as a capacitor plate.

EQUIVALENT CIRCUIT

The equivalent circuit (fig. 2-25) is a two-imensional, simplified representation of the three-dimensional tube. The electron beam flow is from left to right. The capacitance of the backing electrode is indicated, neglecting the parallel resistance that indicates the effect of dielectric surface leakage. From figure 2-25, you can see that electrons will flow into the left-hand plate of the capacitor until that plate is the same potential as the diode cathode (D1) that is 0 volt in this case. The charge on the capacitor is now +2 volts. Electrons from the viewing gun pass through the backing electrode at a maximum density because the backing electrode is at 0 volts on the viewing gun cathode side.

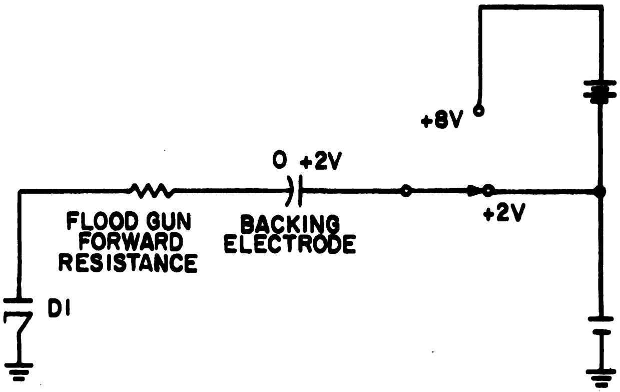

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Figure 2-25.—Equivalent circuit for erasing operation.

Consider the results if this capacitor were suddenly switched from a +2-volt source to a +8-volt supply. Since the charge on the capacitor cannot change instantaneously, the left side of the capacitor becomes 6 volts positive and viewing gun electrons flow until the charge on the capacitor is +8 volts. If at that time the capacitor is switched back to the +2-volt supply, the left side of the capacitor will be at −6 volts (total charge is still +8 volts), the viewing gun will be cut off, and the screen is dark. Now, if the capacitor is switched back to the +8-volt supply, the screen will be illuminated to maximum brightness. When it is returned to the +2-volt position, the screen will be dark. If the switching is rapid between +2 and +8 volts (using a multivibrator for example), the light emitted from the screen will assume some average value between maximum (or saturated) light output and 0, depending upon the percentage of time spent at +8 volts compared to the PRF (duty cycle).

ERASING

You can see from an examination of the equivalent circuit that there is no discharge path for this capacitor or backing electrode other than capacitor leakage. This is true because the viewing gun cathode can supply electrons but cannot take them back; hence, the reason for including a diode in the equivalent circuit. In theory then, a storage tube can be made, which, once cut off in this manner, would remain cut off for extremely long periods of time (days). In a practical storage tube, however, this cutoff condition can be maintained for several seconds to several minutes, depending primarily upon the quality of the vacuum and the storage grid. The apparent storage time can be increased by a process called overerasing that can be done by adjusting the + 8-volt supply or pulse to + 10 or + 12 volts. This is not desirable in most cases, since it reduces the sensitivity of the tube considerably. (There may be times when it would be desirable to trade sensitivity for increased storage time.)

Also, you can see that, as in the case of any resistor-capacitor combination, a certain amount of time is required to affect the charging of the capacitor. The storage grid time constant is typically 5 milliseconds, and it takes about 10 time constants for complete charging (50 milliseconds) of the storage grid. This can be done by turning on the + 8-volt supply for 50 milliseconds. Or, it can be done by turning on the + 8-volt supply 1 millisecond 50 times. Or, it can be done by any combination of pulses and pulse widths whose total comes to 50 milliseconds or more.

After this erasure process is completed, the storage grid is ready to accept information to store. This is performed by means of a writing gun, identical in every respect to a conventional CRT electron gun. The writing gun supplies a finely focused, high velocity electron stream that can be deflected to any area of the storage grid in the usual manner. Figure 2-26 shows the actual tube construction and the relationship of the writing gun to the viewing gun.

Refer to figure 2-26 while reading this section. This high velocity electron beam will strike the storage grid and, because of its high velocity, several secondary electrons will be emitted by the storage grid for every primary electron that strikes it. These secondary electrons are collected by the collector, and the effect is to bring that area of the storage grid out of cutoff. This in turn allows viewing gun electrons to pass through the grid continuously and illuminate the screen. The more

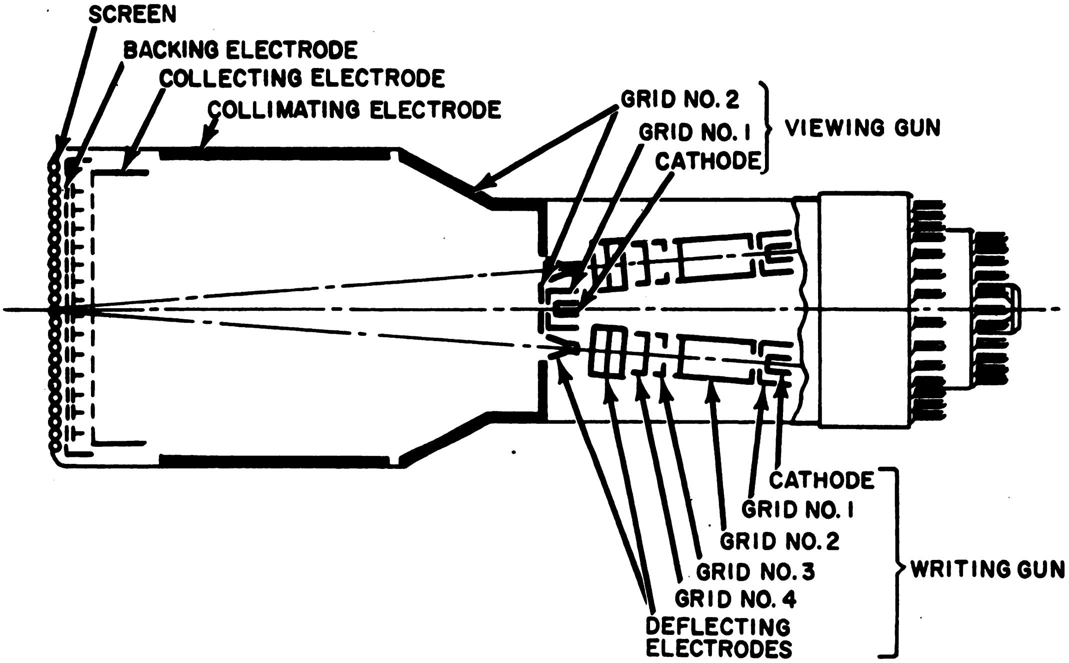

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Figure 2-26.—Cross-sectional view of a DVST.

primary electrons that arrive, the farther out of cutoff the storage grid will go, up to the point where it tries to become positive with respect to the viewing gun cathode. The presence of viewing gun electrons will prevent the grid from going above cathode potential because, if it did, conduction would bring it back down. Hence, you can see that a slow-scanning, low-current density beam will eventually write just as brightly as a high-current density, fast-scanning beam. In fact, a writing gun that is very nearly cutoff will eventually write to full light output if it is allowed to stay in one spot long enough. Wherever this writing beam hits the storage grid, the grid is moved out of cutoff by some amount, depending upon the current density and the dwell time of the beam. Also, where the storage grid is above cutoff, viewing gun electrons pass through the grid and continuously illuminate the screen. It is through this continuous illumination that the high light output is obtained. Otherwise, the light output of a storage tube could be about the same as a conventional CRT of similar design. It is this high light output that permits using the display in relatively high ambient light conditions or, if that is not required, permits the use of filters of various types that would attenuate the light of a CRT to otherwise prohibitively low values.

CONTROLLABLE PERSISTENCE

Earlier in the chapter, you saw that long persistence of the bright display could be obtained, and that this persistence is controllable. In this section of the chapter, you will see how this can be done.

Suppose it is desirable to have approximately 4 seconds persistence. This could be done by writing for 4 seconds, and at the end of that time, apply one 50-millisecond erase pulse. This works! But, it is somewhat disconcerting to the operator to receive a burst of full light output every 4 seconds. In addition, the information presented to the operator would not be continuous since, at the completion of the single erase pulse, the screen would be clean and information would have to be completely rewritten.

A better way to control persistance is to supply a chain of erase pulses continuously in such a manner that changing information (being continuously renewed) would decay only slightly between scans of the writing gun. This can be done by supplying the waveform to the backing electrode that is shown in figure 2-27.

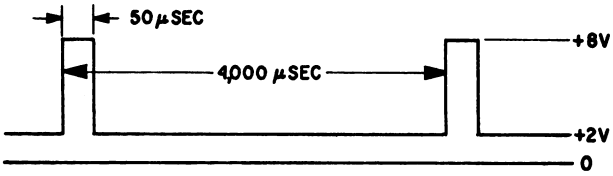

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Figure 2-27.—Erase pulse.

The PRF of this waveform is $1/4000 \times 10^6 =$ 250 pps. Since 50 milliseconds (50×10^{-3} seconds) is required to effect complete erasure, the number of pulses required for erasure is $(50 \times 10^{-3}) \div (50 \times 10^{-6}) = 1000$ pulses. At 250 pps, 1000 − 250 pps or 4 seconds are required to effect complete erasure.

The 50 milliseconds is a tube constant that can be different for different types of tubes and may even vary slightly within tubes of the same type. But, the 50 milliseconds tube constant is typical of many tubes in current production. Persistance can be changed at will by changing either the PRF or the width of the erase pulses or both. The amplitude of the pulse must be carefully adjusted to achieve cutoff without overerasure or undererasure. Overerasure results in severe loss of writing sensitivity since small signals will no longer bring the storage grid out of cutoff. Undererasure will mean old information will never be erased from the display area, resulting in smearing and the loss of dynamic range (ratio of smallest signal to largest signal, usually measured in dB).

The means for changing persistence to suit conditions are not available. Hence, for fast-changing displays, short persistence is desirable. The PRF may be stepped up to 2,500 pps to achieve a 0.4-second persistence. A control could be supplied so that the persistence can be made continuously variable from very short to very long.

SCREEN DAMAGE

By its nature, a storage tube screen is harder to damage by misuse than a conventional CRT. However, some precautions and some peculiarities of the tube should be pointed out.

Where damage to CRT screens results in dark spots due to burned phosphor, similar damage to a DVST results in a bright spot since the burn is usually not on the phosphor but on the storage mesh. This has the effect of shorting the capacitor in the area of the burned spot, and that area can never be cut off. To avoid such damage, the writing gun should never be allowed to collapse to a spot and remain stationary for a long period of time. Similar treatment to a CRT results in nearly instantaneous screen damage. Though it takes a little longer with a storage tube, damage will be done. Since the intensity of a storage tube is controlled by varying the screen potential (+10 kV), merely turning down the intensity control does not prevent this type of damage since it only controls screen current. The writing gun bias must be turned down to prevent this type of damage to the storage grid.

The DVST can also be damaged by writing on areas not illuminated by the viewing gun since there would be no supply of viewing electrons to prevent charging the storage mesh up to a destructively high voltage. Since the capacitor is rated at 35 volts, breakdown occurs when the voltage exceeds some value near its rating. (A sharp-eyed observer notes that as soon as this potential exceeds the collector potential of +265 volts, the secondary electrons will no longer be collected by the collector and further charging toward 2,400 volts would be limited.) Even so, +265 volts would still cause failure.

As you saw earlier, the principal source of light output from the screen is the effect of the viewing gun electron. However, some of the high velocity electrons from the writing guns will pass through to the screen and illuminate it. This illumination is more apparent under some conditions than others (for example, with low screen voltages). The persistence of this *write through* is the same as that built into the phosphor screen and is not controllable. Because of the geometry of the DVST components, the *write through* may appear slightly displaced from its stored counterpart. Because it is characterized by very short persistence, smaller line width, and in most cases lower light output, write through is easily distinguishable from the stored information and causes little concern, unless the operator is not familiar with its cause.

Some of the advantages offered by the DVST may not be so apparent upon first examination. A very important advantage is the saving in total weight and size of an indicating system using a DVST. For example, because the backing electrode is very nearly at ground potential, it forms an effective shield between the writing gun deflection system and the +10,000-volt screen potential. This factor, added to the relatively low writing gun voltage required for proper operation, allows subminiature tubes to be used in the writing gun deflection system. Similar size savings are to be realized in the writing gun power supply.

In addition, because of the characteristics of the backing electrode, it is unnecessary to drive the writing gun grid to zero bias to obtain maximum light output, as in the case with the conventional CRTs. Additional savings in weight, space, and power consumption are realized by the design of the video amplifier. Again, subminiature tubes become practical.

As a result, a given indicating system can be packaged so that it is shorter in length, smaller in cross-sectional area, and lighter in weight. This requires less primary and secondary power, yet provides target detection enhancement and display brightness that would normally not be possible with conventional CRT devices.

PULSE EXPANSION AND COMPRESSION

Pulse compression (nicknamed Chirp Radar) is incorporated in all types of radar. It improves a radar's performance by a factor as high as several hundred. In many cases, computers are used to display information rather than the typical PPI display. Target symbols are used to display target information, range, bearing and so forth.

ADVANTAGES

Some of the advantages discussed in this section are extended range with improved range resolution, height finding capabilities, immunity from ECM jamming, increased signal-to-noise ratio, and target velocity.

Extended Ranges

The pulse expansion and compression technique allows for extended range. An important factor in any radar's maximum range is the envelope power. Envelope power is found by multiplying the pulse width times the peak power. A typical search radar has a pulse width of 2 μsec and a peak power of 2.5 megawatts. This will produce an envelope power of 5 watts/sec. A typical pulse compression radar will have a pulse width of 10 μsec and peak power of 1 megawatt which will produce an envelope power of 10 watts/sec. Since range is partially determined by the transmitter, an increased range over the conventional pulse radar is possible.

Improved Range Resolution

Range resolution is the minimum distance by which two targets must be separated in order to appear as two separate displays on a scope. This separation is largely determined by the pulse width of the echo being returned to the receiver. In a typical conventional radar with a 2-μsec pulse width, range resolution would be 1,000 feet. In the pulse compression radar, the 10-μsec returned pulse is compressed to 0.1 μsec before being applied to the receiver. Therefore, the range resolution is 0.1 × 500 or 50 feet. This improved range resolution is accomplished without affecting maximum range because the envelope power is not changed.

Height Finding Capabilities

Pulse compression can be used to determine height. This is based upon the ability of the radar to receive multiple-path returns from a single target. With sufficient power, receiver sensitivity, and range resolution, the system can distinguish between three echo returns (fig. 2-28). By measuring the time difference of the three returns and comparing the altitude of the radar transmitter, the computer can determine the target altitude. Only the pulse compression radar has both the power and range resolution necessary for this type of altitude determination.

ECM Deception

The pulse compression radar depends upon the phase and frequency characteristics of the transmitted pulse to determine whether or not to accept a returned signal. If the phase and frequency do not match the transmitted pulse, compression will not take place, and the signal will not pass through the receiver.

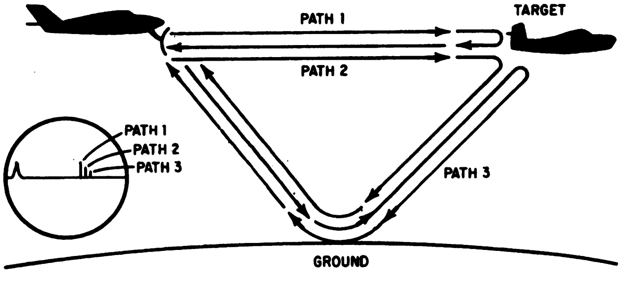

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Figure 2-28.—Multiple-echo paths.

Signal-to-Noise Ratio

The matched filter responds to the definite phase and frequency characteristic of the transmitted signal and the attenuation of other signals. The pulse actually applied to the receiver has a signal content much higher than its content of random noise. The signal-to-noise ratio of the system is improved by a factor equal to the compression ratio over conventional radar.

Target Velocity

Target velocity can be rapidly determined by the use of a computer and sideband inversion. If a signal receives up Doppler, after sideband inversion the shift will appear as down Doppler. By shifting the local oscillator frequency above and below the returned echo on alternate pulses, the Doppler can be changed from up to down alternately with each transmitted pulse. This produces a shift equal to twice the normal Doppler shift and makes it possible to determine target velocity in a time equal to two PRT.

PULSE EXPANSION

In the pulse expansion operation, a 0.1-μsec pulse is expanded to 1 μsec. Then, a 10-μsec chain of pulses for transmission is formed through the use of stagger delay (frequency) 1-μsec pulses. The overall operation is to generate a 0.1-μsec pulse and, after expansion, transmit a 10-μsec pulse.

Spectrum Generation

RF energy is generated by a coherent master oscillator (COMO) that is gated with a square wave of the desired time duration. For discussion purposes within this section, a COMO with a center frequency of 100 MHz is gated for 0.1 μsec at a PRF of 300 Hz. When this pulse is produced, it contains not only the basic frequency, but also many other frequencies within a spectrum as shown in figure 2-29. While the difference between each frequency is determined by the PRF, the pulse width determines the bandwidth; therefore, the number of frequencies within the spectrum is controlled by both PRF and pulse width.

In figure 2-29, the frequency that has the largest amplitude is the resonant frequency of the signal source by means of which this spectrum was created. Numerous other frequencies result on either side of f_o. Those above f_o will be f_o plus one PRF, f_o plus 2 PRFs, and so forth. At this rate, numerous different frequencies are present, each 300 Hz apart, and each smaller in amplitude as

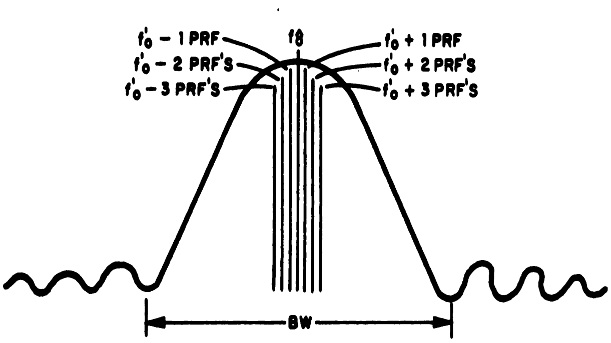

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Figure 2-29.—COMO output.

these frequencies approach the upper bandwidth limit.

Those below f_o are f_o minus 1 PRF, minus 2 PRFs, and so forth. At this rate, numerous different frequencies would be present, each one lower in frequency by 300 Hz, and each one lower in amplitude as the lower bandwidth limit is approached.

Since the COMO is gated for 0.1 μsec of time, it generates a spectrum with a bandwidth of 20 megahertz. Bandwidth is determined by dividing the pulse width into one.

NOTE: In order to receive and to reproduce satisfactorily rectangular pulses equal in amplitude to noise voltage, the receiver bandwidth (in hertz) should be approximately 2 divided by the pulse width (in seconds). Therefore, a 0.1-μsec pulse width generates a 20-megahertz spectrum bandwidth. Because each of the frequencies between the bandwidth is 300 Hz apart, over a 20-megahertz bandwidth, there are 66,666 different frequencies contained in this frequency spectrum.

Matched Filters

The matched filter discussed in this section consists of ten channels. Each channel has one or more amplifiers (one of which must be tuned) and a delay line as shown in figure 2-30. Each channel has individual gain and frequency

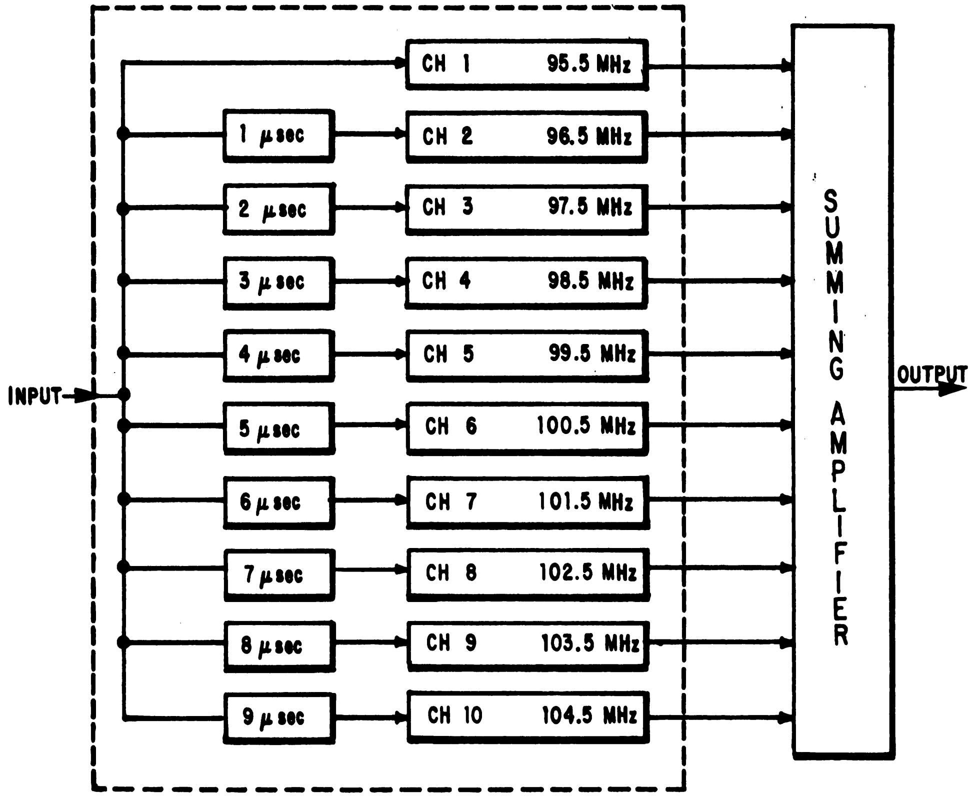

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Figure 2-30.—Matched filter assembly block diagram.

controls with a bandwidth of 1 MHz. The amplifiers are tuned to successive frequencies 1 MHz apart so that their response curves overlap at their half-power points as shown in figure 2-31. The entire filter bandpass is 10 MHz from the center of the above described spectrum. The filter now responds to 33,333 different frequencies with each channel responding to 3,333 different frequencies. The ten sections, with their respective delay lines, are connected with parallel input, and all outputs are connected to a summing amplifier to produce a single output.

The entire frequency spectrum bandwidth (20 MHz) is applied to the input of each of the ten channels through the delay line (except channel 1 which has no delay line). Each of the ten channels is tuned so it covers only a small part of the total frequency spectrum. Since there are only ten channels, each with a bandwidth of 1 megahertz, only one-half of the overall spectrum is covered. Therefore, one-half of the spectrum is not passed through the matched filter because it is not within the half-power points of any of the 10 channels.

This is necessary because the amplitude of the different frequencies is too great between the maximum and minimum. If the frequencies outside of the channel spectrum half-power points are rejected, the amplitude difference between f_o and f_1 or f_2 is now only 3 dB. This allows the gain of the channels to be within practical limits.

As you have seen, the numerous frequencies within the entire spectrum bandwidth were separated from each other by 300 Hz, and since

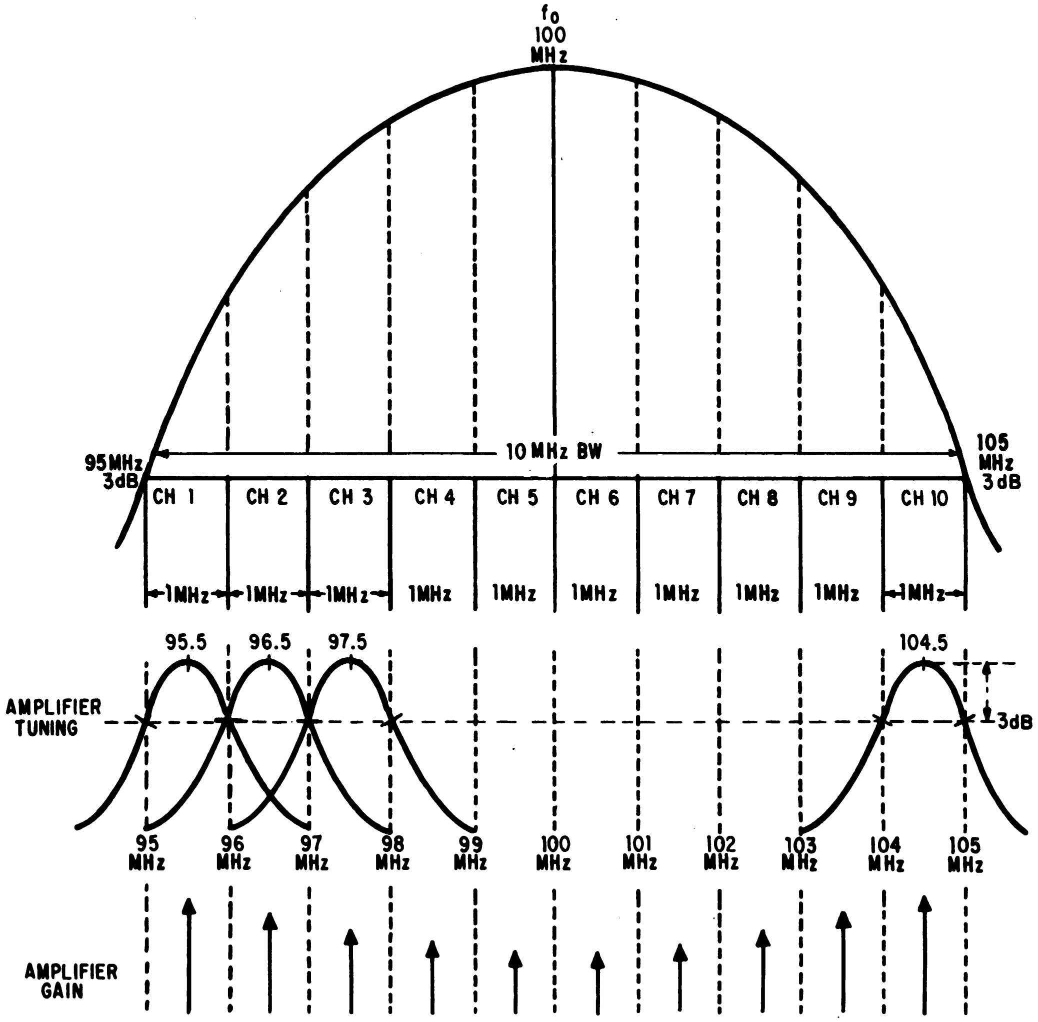

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Figure 2-31.—All channel response curves.

the overall bandwidth was 20 MHz, there were 66,666 different frequencies. The matched filter is tuned to react to only half of the overall bandwidth, so the filter will receive only 33,333 different frequencies. This, in turn, is covered in ten different steps by the ten filters, so each individual filter will receive only 3,333 different frequencies. For ease of explanation, only 3,300 frequencies will be used in the remainder of this chapter.

EFFECT OF A TUNED AMPLIFIER ON FREQUENCIES WITHIN ITS BANDWIDTH.—In a parallel resonant tank circuit, the voltage and current are in phase at f_o. At frequencies below f_o, the circuit appears inductive (X_L) and voltage leads the current. The farther below f_o the frequency is, the more inductive the tank appears, and the greater lead voltage has over current. At f_1, the voltage leads the current a maximum usable amount.

At frequencies above f_o, the circuit appears capacitive by the amount that the frequencies differ from f_o. At f_2, the current leads the voltage by the maximum usable amount. Since each tank circuit in the matched filter has a bandwidth of 1 megahertz and receives 3,300 different frequencies, approximately 1,650 of them are above f_o and 1,650 are below f_o. To those above f_o, the tank will appear capacitive. To those below f_o, it appears inductive. To the one frequency at f_o the tank circuit appears purely resistive.

The tuned amplifier is designed so that signal voltages are coupled out rather than signal current. To determine which signal voltages will be developed by the tank first, a reference must be used. This reference is the voltage and current that occur at f_o of the tank, and which are in phase because the tank is resistive.

The 1,650 frequencies (above and below f_o) are applied to the tank circuit (tuned amplifier) at the same time. The voltage at the frequency f_1 of the tank will lead the f_o current by the amount of X_L that this frequency sees.

Frequencies in between f_1 and f_o will lead by a lesser amount because the tank circuit appears less inductive to these frequencies. These voltages will have been advanced in phase (or time) in respect to the voltage at f_o of the tank.

The voltage of the frequency f_2 is retarded in phase (or time) because the tank circuit appeared capacitive to that frequency. Before any voltage can be developed, current has to begin to flow first (because current leads voltage across a capacitive circuit). Voltages at frequencies in between f_2 and f_o saw less X_C; therefore, they were retarded less.

The output from this tuned amplifier is a series of signal voltages at 3,300 different frequencies. The lowest frequency (f_1) occurs first because it was advanced the most in time. The highest frequency (f_2) occurs last because it was retarded the most in time.

The Q of the tank circuit is selected so the voltage at f_1 advanced by 0.5 μsec, and the voltage at f_2 is delayed or retarded by 0.5 μsec. The time difference between the time when the frequency at f_1 is developed and the time when the frequency at f_2 is developed is 1 μsec. Since there are 3,300 different frequencies produced and coupled out of the tuned amplifier in a period of 1 μsec, the time delay between each of these different frequencies is 0.00031 μsec. As shown in figure 2-32, the first frequency to leave the tuned amplifier would be the frequency at f_1, and each 0.00031 μsec thereafter another frequency would be developed and coupled out until the frequency of f_2 is developed 1 full μsec later.

Since frequency is the reciprocal of time, you can see that the output from each channel (1 μsec in time) is 1 MHz wide in frequency. What has been done is to take 3,300 different frequencies, each one in phase, and time delay or time advance each one by a different amount. This process has created a waveform that begins to appear as a linearly swept FM wave. It is known as time dispersion or phase dispersion.

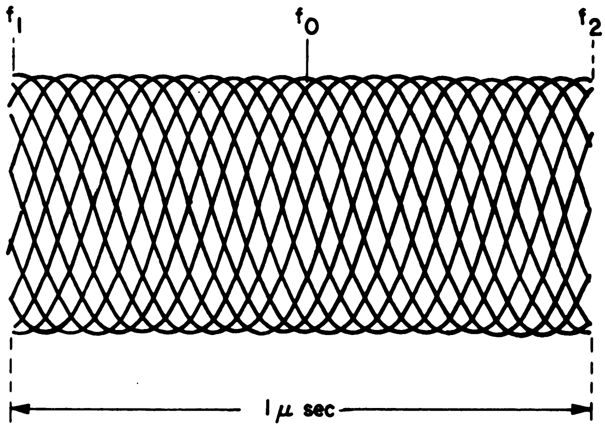

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Figure 2-32.—Individual channel frequency output (expansion).

COMBINED OUTPUT OF THE MATCHED FILTER.—Figure 2-30 shows the entire frequency spectrum applied to the input of each of the ten filter channels simultaneously, but through a delay line for channels 2 through 10. This means that channel 1 receives its input at the instant the spectrum is applied to the input of the filter. Channel 2 does not receive its input until later in time due to the delay line. Channel 3 receives its input still later in time than channel 2. This process continues so that channel 10 receives its input last because the delay line in its input offers the largest amount of delay.

Since channel 1 received the frequency spectrum first, it produces an output first. Channel 1 is tuned to 95.5 MHz and has a 1 megahertz bandwidth. It produces in its output only that part of the spectrum from 95 MHz to 96 MHz. The frequency to first appear at the output of channel 1 is the lowest frequency within the bandwidth of the tuned amplifier. This is because the lowest frequency receives the greatest phase or time advance because of X_L of the tank circuit at that frequency. The last frequency to leave channel 1 is the highest frequency within its bandwidth. This frequency receives the most time or phase delay because of X_C of the tank circuit to that frequency. Each of the remaining 3,300 frequencies are either advanced or retarded by a lesser amount, so that the time required for channel 1 to reproduce all 3,300 frequencies is 1 μsec.

As channel 1 is finishing its output waveform, channel 2 is just receiving the spectrum at its input (because the spectrum was delayed 1 μsec by the delay line). Channel 2 is resonant to 96.5 MHz, has the same 1-MHz bandwidth, and reproduces that part of the spectrum from 96 MHz to 97 MHz. The lowest frequency within the bandwidth of channel 2 is reproduced first because it received the greatest advance by X_L. The highest frequency is reproduced last because it was delayed by X_C. Channel 2 requires 1 μsec to produce its full 1-MHz output. Two μsec in time have now elapsed.

As channel 2 finishes producing its output, channel 3 receives the frequency spectrum at its input through the 2-μsec delay line. Channel 3 picks up in frequency where channel 2 left off and provides another 1-MHz part of the output for a period of 1 μsec.

This process continues until channel 10 receives the frequency spectrum at its input after being delayed by the 9-μsec delay line. It then produces the tenth part of the total output waveform that is resonant from 104 MHz to 105 MHz. It is also 1 μsec wide.

The lowest frequency of channel 1 (95 MHz) is produced, and 10 μsec later, the highest frequency of channel 10 (105 MHz) is produced. This is shown in figure 2-33.

Each of the ten channel's output waveforms is combined in the summing amplifier to produce the waveform shown in figure 2-33. This waveform sweeps a 10-MHz band of frequencies during a time of 10 μsec within a linear change of 1 MHz/1 μsec. This type of waveform is called a linear frequency modulated pulse. The matched filter that produces this type of waveform is called a linear frequency modulated pulse (LIFMOP) filter. This LIFMOP waveform

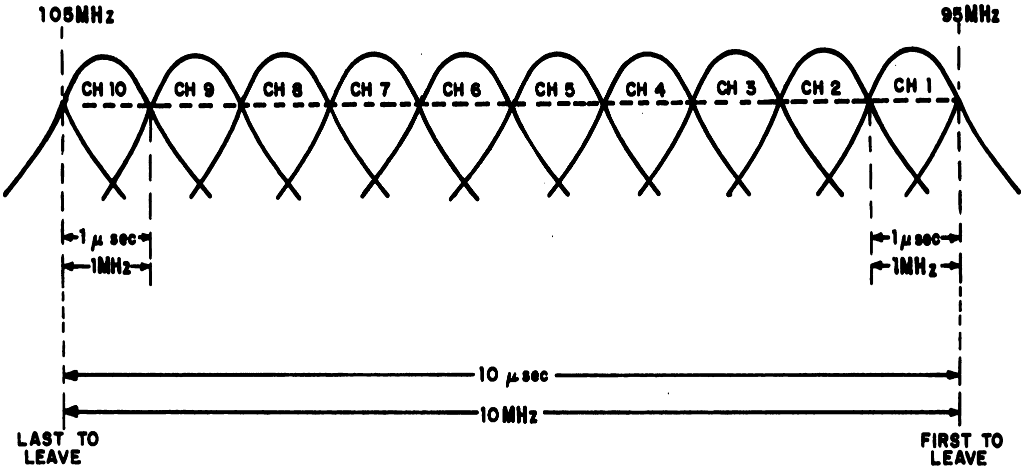

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Figure 2-33.—Summing amplifier output.

contains approximately 33,000 different frequencies, each one being in a very definite time and phase relationship to the others.

The output from each channel must be equal in amplitude. To ensure equal amplitude from each channel, an oscilloscope is connected to observe the output of the summing amplifier. The amplitude adjustment (screwdriver adjustment) is set on each channel so that the output from each amplifier is equal in amplitude. With the oscilloscope connected to the same point, the frequency adjustment (a technician's adjustment) is set so that the output of each amplifier coincides with the output of the amplifiers on either side of it with no interruption of the pulse. When any of the amplifiers are changed, both of these adjustments must be performed.

The LIFMOP waveform may be transmitted at these frequencies, or it may be passed through frequency converters to increase the frequency to whatever is desired to be transmitted. Normally, it is amplified by several RF amplifiers prior to being transmitted. Of necessity, these RF amplifiers have a very broad bandwidth and linear frequency response to avoid any type of distortion of the LIFMOP waveform. The waveform shown in figure 2-33 leaves the summing amplifier with some amplitude variations. It is desirable that the transmitted waveform have no variations of amplitude. Normally, the waveform is passed through a limiter before transmit to remove these amplitude variations.

The transmitted pulse is rectangular, swept in frequency over 10 MHz, and 10 μsec in duration. It is composed of the combined outputs of all ten filters.

PULSE COMPRESSION

Pulse compression is basically the inverse of pulse expansion. This is, when a 10-μsec target return is received, it is compressed so that the receiver output is a 0.1-μsec echo.

Echo Return from a Target

Let's assume that a target is located a distance from the receiving antenna so that 100 μsec of travel time is required for the return echo to reach the receiver antenna. The lowest frequency was the first to leave the transmitter and the first to strike the target. Thus, the lowest frequency is the first frequency picked up by the receiving antenna. (It will be returned 100 μsec after it strikes the target.) The highest frequency transmitted did not leave the transmitter until 10 μsec later. It did not strike the target until 10 μsec after the lowest frequency struck the target. Therefore, it was not returned to the receiving antenna until 10 μsec after the lowest frequency was received.

Now look at figure 2-34. You see that a definite time versus frequency relationship exists

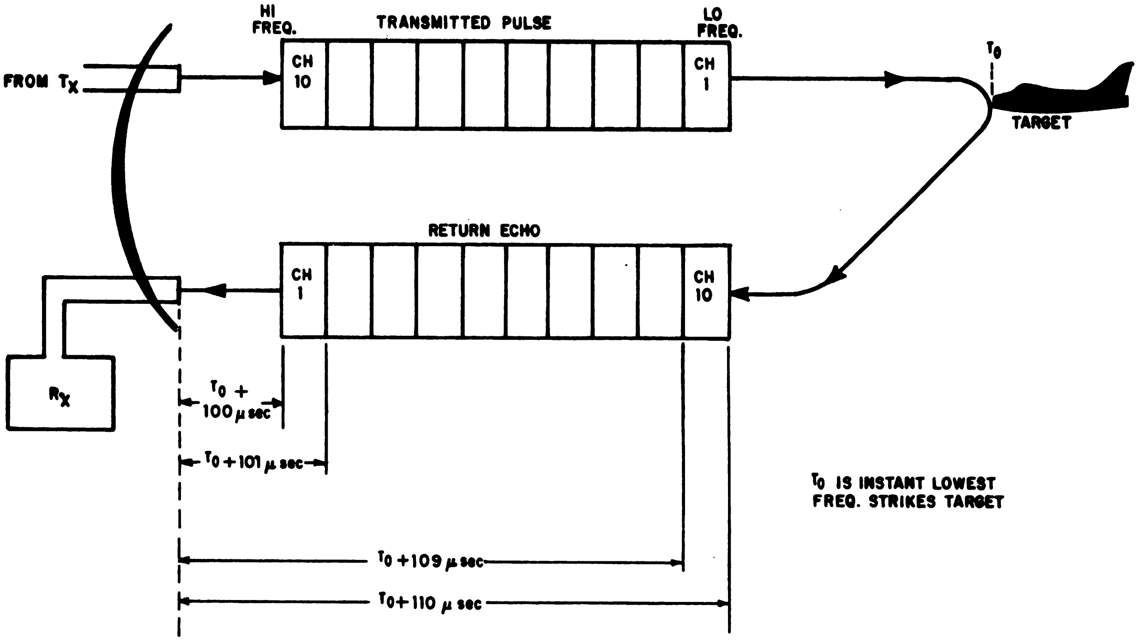

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Figure 2-34.—Time function of transmitted pulse.

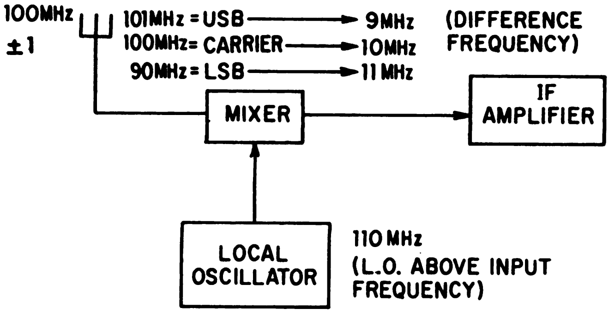
during the 10 μsec that the returning echo is felt on the receiver input. The frequency can be determined at any time. Therefore, the channel receiving a signal can be determined. For instance, at T_o plus 106 μsec, the frequency which will enter channel 6 is just arriving at the receiver antenna. This means that the frequencies affecting channels 1 through 5 have already arrived, and channels 7 through 10 are yet to come.

The returned echo is applied to the matched filter as it is now (lowest frequency first) by action of the L and C of the tanks. The filter tends to expand the signal again rather than compress it, as is desired. For the pulses to be compressed, the frequency relationships must be reversed. That is, the returned echo must be turned around so that the highest frequency enters the matched filter first, and the lowest frequency enters last, or 10 μsec later. This is easily achieved by sideband inversion.

Sideband inversion is a process of inverting the frequencies contained in the upper and lower sidebands during the process of frequency conversion. This process occurs any time the local oscillator is tuned above the frequency to be converted, and the difference frequency is selected.

NOTE: Before you read the following section, look at figure 2-35. You should be aware that the frequency values used in this figure are arbitrary. They were selected to illustrate sideband inversion.

From figure 2-35, you can see that when the upper sideband (101 MHz) passes through the mixer, the difference frequency produced is 9 MHz. When the lower sideband frequency (99 MHz) is converted, the difference is 11 MHz. Thus, the highest incoming RF produces the lowest difference frequency, and the lowest RF produces the highest difference frequency. In the case of the pulse compression radar under discussion, the returned echo is passed through a frequency conversion stage for the purpose of sideband inverting the frequencies. The lowest frequency that was first returned becomes the highest frequency after sideband inversion (95 MHz emerges as 105 MHz). The highest frequency (105 MHz) returning last emerges from the mixer as 95 MHz. Because of this process, the entire frequency content of the returning pulse is reversed. After this inversion, the echo is now ready to be applied to the matched filters for pulse compression.



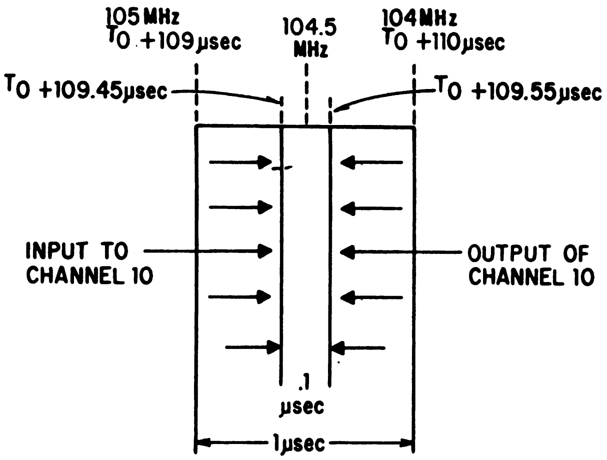
223.111

Figure 2-35.—Sideband inversion block diagram.

Action of Matched Filter on the Returned Echo

The returning pulse (after sideband inversion) is once again applied to the parallel inputs of all 10 matched filter channels. The difference between the input to the matched filter (now on the pulse compression function) and the input for the pulse expansion function on transmit is that of pulse expansion—all frequencies (each one in phase) were present at *each* channel at the *same time*. But on pulse compression (or receive), the frequencies arrive *one at a time*, each one separated from the others by a small phase and time difference. The first frequency to arrive (T_o plus 100 μsec) is the highest input frequency to the filter after conversion. Ten μsec later (at T_o plus 110 μsec), the lowest input frequency after conversion arrives at the filter. You should note that as each individual frequency arrives, it is present at the input to each one of the ten channels simultaneously. Refer to figure 2-36 as you read the rest of this section.

The highest frequency (after conversion), being the first to arrive, is applied directly to the matched input filter. Since this frequency is within the bandpass of only channel 10, it affects only channel 10. Before it can be applied to the tuned amplifier of channel 10, it receives a 9-μsec delay. Therefore, this frequency finally is present at the tuned amplifier of channel 10 at T_o plus 109 μsec. For the next 1 μsec of time, all of the frequencies within the band pass of channel 10 will arrive and be processed. The highest frequency (105 MHz)



223.112

Figure 2-36.—Individual channel compression.

at T_o plus 109 μsec is above the resonant frequency of channel 10 (104.5 MHz), so the tank circuit appears capacitive to that frequency.

The tank circuit has the same effect on frequencies above its resonant frequency that it had during pulse expansion. It delays these frequencies by an amount proportional to the amount of capacitive reactance the tank offers to that frequency. The 105-MHz signal, being the farthest away from the f_o of the tank, will be delayed the most (approximately 0.45 μsec).

The next frequency to arrive at the tank is slightly later in time and lower in frequency, and it receives slightly less delay than did 105 MHz. When 104.5 MHz arrives (at T_o plus 109.5 μsec), the tank simply passes it exactly as it is. The rest of the frequencies within the bandpass of channel 10 are lower than the f_o and see an inductive reactance. This advances these lower frequencies by an amount proportional to the X_L of the tank. The 104 MHz signal (the lowest frequency within the channel 10 bandpass) sees maximum inductance and is advanced approximately 0.45 μsec. The end result is that the bandwidth of frequencies of channel 10 (1 μsec wide) is compressed to 0.1 μsec. It comes out of channel 10 at T_o plus 109.45 μsec to T_o plus 109.55 μsec (fig. 2-36).

The band of frequencies processed and compressed by channel 10 arrived at the receiver antenna from T_o plus 100 μsec to T_o plus 101 μsec. From T_o plus 101 μsec to T_o plus 102 μsec, the frequencies within the bandwidth of channel 9 arrive at the receiving antenna. To get to the tuned tank of channel 9, they must pass through the 9-μsec delay line. Then, at T_o plus 109 μsec, the first frequency for channel 9 (104 MHz) arrives. This frequency is higher than the resonant frequency (103.5 MHz), so it is retarded approximately 0.45 μsec, and it is reproduced in the output of channel 9 at T_o plus 109.45 μsec. The lowest frequency to channel 9 (103 MHz) sees maximum inductance and is advanced approximately 0.45 μsec. Channel 9 produces its output from T_o plus 109.45 μsec to T_o plus 109.55 μsec, or during the same time channel 10 was producing an output.

This process continues as each one of the channels receives its band of frequencies 1 μsec apart in time, but produces its output at the same time as each of the other channels. Finally, at T_o plus 109 μsec, the first frequency to pass through channel 1 arrives at the receiving antenna and is felt directly on the tuned tank in channel 1 since channel 1 has no delay line. Channel 1 then produces an output at exactly the same time as the previous nine channels.

The output circuit of each individual channel is fed into summing amplifiers where all ten outputs are combined. Because each channel produces an output at exactly the same time and for exactly the same time duration, all ten outputs add directly and appear at the output of the summing amplifiers as one pulse 0.1 μsec in duration. The entire 10-μsec return echo has been compressed to 0.1 μsec. It is now ready to be detected and sent to the indication devices.

The ratio between the pulse width of the transmitted pulse and the returned compressed target echo is expressed as the compression ratio. It is determined as follows:

$$\text{Compressed ratio} = \frac{\text{pulse width of expanded pulse}}{\text{pulse width of compressed pulse}}$$

The compression ratio of the radar being discussed is:

$$\text{Compression ratio} = \frac{10\ \mu\text{sec}}{0.1\ \mu\text{sec}} = \frac{100}{1} = 100{:}1$$

This expression is considered a figure of merit for a pulse compression-type radar.

During the process of pulse compression, some apparent amplification occurs across the matched filter. This happens because of the energy content and time duration of the returned echo. The 10-μsec pulse arrives with a certain volt/ampere energy content, but it is compressed in time down to a pulse of 0.1 μsec. Assuming none of the energy content was lost across the matched filter, the same amount of energy must still be present in the compressed pulse. If the pulse width narrows, the amplitude of the compressed pulse will increase. This increase is the same as the compression ratio. In the radar under discussion, the pulse is compressed by a ratio of 100:1. So, the amplitude of the compressed pulse is 100 times larger than the amplitude of the received target return. Yet, it still contains the same energy content.

You should note that in a practical radar using pulse compression, it is very difficult to get the returned energy compressed back to the same pulse width that was used in the pulse expansion sequence. As you know, there are many thousands of frequencies (each different by one PRF) in the transmitted pulse. Each of these frequencies bears a very definite time/phase relationship to each other. In order for the returning echo to be compressed back to the original pulse width, each one of the frequencies must be present and must bear the exact same time/phase relationship that it did upon leaving the transmitting antenna. Due to atmospheric conditions and waveguide vibration, some atmospheric modulation occurs between pulse expansion and pulse compression. Some of the frequencies will be changed. So, it will not be easy to reconstruct the original pulse. In the radar under discussion, typically the 10-μsec returned echo is compressed into a 0.1-μsec pulse, for a compression ratio of 50:1. This means that if the entire energy content is maintained across the filter, the amplitude of the compressed target video would be 50 times larger than the amplitude of the returning echo.

SIGNAL-TO-NOISE RATIO

The noise which might exist in the band of frequencies covered by the radar are at random frequencies and bear random phase relationships to each other and to the returning target echo. Any of these frequencies that exist within the bandpass of the matched filter passes through the filter but are not affected by the filter. That is, they are neither expanded nor compressed because of their random relationship. So, they emerge at the same amplitude at which they went in, while the return echo emerges enlarged in amplitude by the amount of the compression ratio. Radars using pulse compression are generally considered to have an increase in the signal-to-noise ratio across the matched filter approximately equal to the compression ratio. This is in addition to the signal-to-noise ratio increase that might be gained by using suitable receive input amplifiers.

ECM CONSIDERATIONS

A pulse compression-type radar is very difficult to jam. The primary reason for this is the characteristics of the matched filter. To overcome the target video, noise jammers would have to produce enough noise signal so the noise at the receiver antenna would be greater than the returning target echo by the amount of the compression ratio. This is easily eliminated by insertion of circuits between the antenna and matched filter that automatically reject abnormally large signals. This method is currently in use in certain long-range search radars in operation with the fleet. Repeater jammers (to override the actual target return) would have to generate a spectrum containing exactly the same frequencies, each bearing the exact same phase and time relationships as that of the transmitted pulse. Even if this were possible (some types of ECM equipments simply amplify whatever their antennas receive), the ECM signal would be rejected since it would be larger in amplitude than the valid received target return. This repeater jammer could have no more delay between the time it received the transmitter's signal and the time that it retransmitted this same amplified signal than the time duration of the compressed pulse as it comes out of the matched filter. When the delay is greater than the pulse width of the compressed pulse, the indication device (computer) would see two distinct returns: one would be the target and the other would be the ECM signal. Even if the delay was less than the pulse width of the compressed pulse, the computer would still see the target return first, then a sudden increase in amplitude as the ECM signal came through. The computer would automatically reject ECM return, but it would see the target return. Chaff jamming is easily countered by the incorporation of circuits that reject abnormally slow moving targets such as chaff, corner reflectors, balloon borne devices, and so forth.

To further increase the difficulty in jamming the pulse compression type of radar, the PRF could be made to vary at a random rate. This causes each and every frequency in the transmitted pulse to change slightly each time the transmitter fires. Unless the returning echo contains exactly the same frequencies that were just transmitted, the matched filter rejects them.

CONTINUOUS WAVE DOPPLER MTI

The basic continuous wave (CW) Doppler moving target indicator (MTI) radar detects moving targets in areas or regions of heavy clutter, down to zero range. The moving targets that are detected are those having changing range rates. Crossing targets (moving targets not having a changing range rate) are not detected.

The operation of a CW Doppler MTI radar relies on the phenomenon that a moving target changes the frequency of the transmitted signal. The difference in frequency between the transmitted signal and the returning signal is termed the Doppler frequency. The usefulness of the CW-type Doppler radar is limited because the range of targets cannot be determined.

A block diagram of a basic CW Doppler MTI radar circuit is shown in figure 2-37. The radar system transmits a CW signal from the radar antenna to a moving target. The fact that the target is moving causes the signal to be changed in frequency with respect to the transmitted signal. This change in frequency of the returned signal produces a constantly changing phase relationship with the transmitted signal. A nonmoving target produces a fixed phase difference between the two signals, but a moving target causes a constantly changing phase difference. This provides the means of distinguishing between moving and fixed targets.

The returned signal is received by the receiving antenna, and together with a sample of the transmitter signal, is applied to a phase detector. In the phase detector, the phase of the received signal is compared to the phase of the transmitted signal to produce an output. Nonmoving targets have a fixed phase difference and therefore produce a constant (dc) output. The constantly changing phase difference in the signal of a moving target produces an output that is constantly changing or fluctuating.

The high-pass filter rejects the dc components of the video representing stationary targets and passes the video fluctuations produced by moving targets. The fluctuating signals are then amplified and applied to an indicator as MTI video.

PULSE-MODULATED DOPPLER MTI

The pulse-modulated Doppler MTI radar detects one or a multiplicity of moving targets in the heaviest of ground clutter. It can be used to measure the velocity and range of targets. Crossing targets are nonmoving as detected by this type MTI. A block diagram of a typical

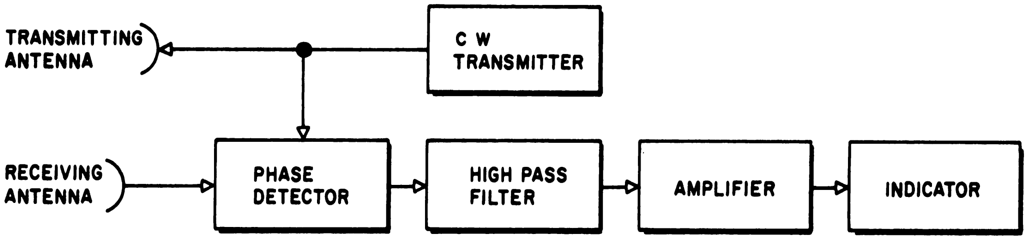


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Figure 2-37.—Basic CW Doppler MTI radar circuit block diagram.

pulse-modulated Doppler MTI radar is shown in figure 2-38.

The pulse-modulated Doppler MTI radar circuit uses filters to remove stationary targets in the same manner as in the basic CW Doppler radar circuit. However, the CW Doppler radar can function to zero range while the pulse-type Doppler radar cannot. The pulse-modulated Doppler radar can be used in areas that normally produce heavy ground clutter. It is useful for measuring both target range and velocity. The pulse Doppler method imposes no restriction on the relative values of either Doppler or recurrence frequencies.

There is an inherent undesirable effect in the MTI. This occurs when the Doppler frequency is equal to a multiple or submultiple of the transmitter frequency. In this case, the resulting signal is unchanging in either amplitude or polarity, and the moving targets producing these multiple frequencies are eliminated the same as a stationary target. The radar system is said to be blind to targets moving at this speed; these speeds are called *blind speeds*.

The radar oscillator produces the transmission carrier frequency (f_o) and applies this frequency to both the modulator and second mixer circuit. The modulator produces the transmitter pulses, which pulse-modulates the carrier frequency, and triggers the transmitter that allows transmission of the signal.

The returned signal pulse (f_o) (plus or minus the Doppler signal (f_d) from any moving target) is received by the antenna and applied to the input of the mixer via the waveguide. In the case of incoming targets, the Doppler frequency (f_d) is added to the returned signal; for outgoing targets f_d is subtracted from the returned signal. The resulting signals are then fed to the first mixer circuit.

The second mixer circuit which receives the transmission carrier frequency (f_o) also receives a signal from the 30-MHz oscillator. These signals are mixed and the lower sideband (difference frequency) is passed and applied as f_o − 30 MHz to the first mixer circuit. In the first mixer, f_o − 30 MHz is mixed with the received signal ($f_o \pm f_d$). The resultant output frequency (30 MHz ± f_d) is applied to the IF amplifiers. The amplified output is detected and applied to the clutter filter as nonfluctuating video for nonmoving targets and fluctuating bipolar video for moving targets. The clutter filter suppresses, by frequency rejection, the clutter signals not having the video frequency responses of either moving or almost nonmoving targets.

The noise and Doppler filter network provides additional filtering of target video to remove the undesirable video responses. The

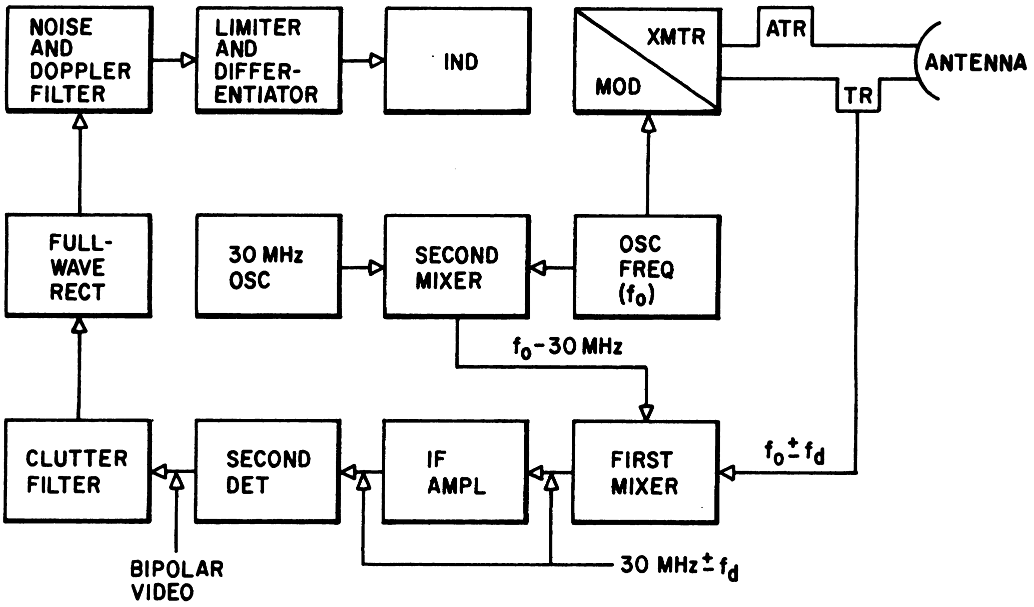

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Figure 2-38.—Pulse-modulated Doppler MTI radar block diagram.

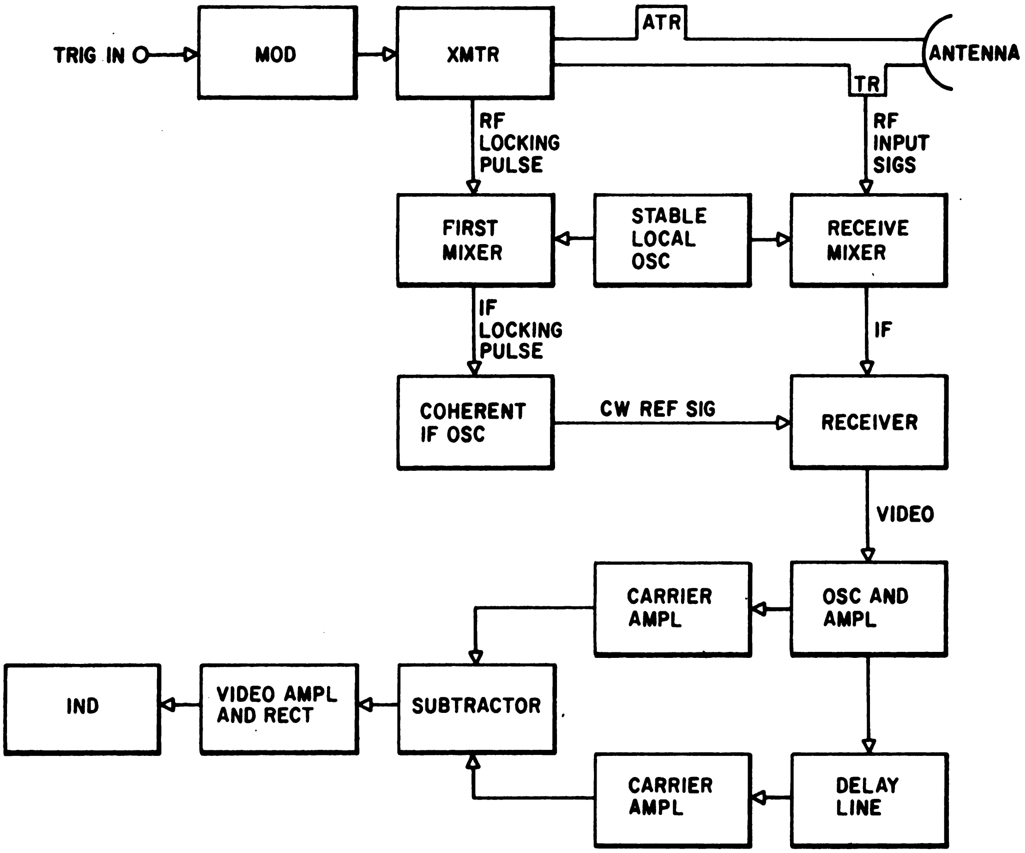
limiter-differentiator network removes excessive amplitude peaks of the signal and differentiates the pulse. The differentiated pulse is then presented on a CRT indicator for display.

COHERENT MTI

Coherent MTI responds mainly to moving targets. Only the moving targets having changing range rates are selected for presentation on an indicator, normally an A-scope. A block diagram of a typical coherent MTI circuit is shown in figure 2-39.

Unlike the basic CW Doppler or the pulse-modulated Doppler circuits that use filters to eliminate stationary targets and clutter, the coherent MTI detects the difference in phase between the echo signal and a reference signal whose phase is in step with the transmitted signal. The phase of the echoes from moving targets changes from pulse to pulse. When beat against the reference signal, a change in amplitude of its detected video occurs from pulse to pulse. Nonmoving targets produce detected outputs having relatively equal amplitudes from pulse to pulse because their phase does not change from pulse to pulse. A cancellation circuit is then used to remove the nonfluctuating video of nonmoving targets and pass the fluctuating video responses for display of only the moving targets.

The coherent IF oscillator (commonly known as COHO for coherent oscillator) provides a CW reference signal with which to beat the received echo signals. Since the transmitter starts with random phase from pulse to pulse, it is necessary to match the phase of the COHO to that of the transmitter at each transmitted pulse. This is done by sampling the transmitted signal (RF locking pulse) and using it (after conversion to the IF locking pulse) to control the phase output of the COHO. (This process is called *locking* the phase of the oscillator, or making it *coherent*.) Likewise, the IF of the received echo signals must be locked in phase if their phases are to be in-step with the transmitted signal. This is the purpose of the



223.42

Figure 2-39.—Coherent MTI radar block diagram.

stable local oscillator and first mixer combination. Any change in phase of the echo IF, as a result of a phase change from the stable local oscillator, is also reflected in the IF locking pulse. The overall result is an echo IF coherent in phase with the CW reference signal from the COHO. This occurs only if the echo IF was produced from a nonmoving target. A moving target changes the phase of the transmitted signal that results in a change in phase of its echo signal. These phase changes are out-of-step with the phase of the CW reference signal and cause a change in amplitude when detected as video in the receiver.

The detected pulses from the receiver are applied to modulate the frequency produced by an oscillator. This oscillator produces a carrier frequency (normally about 15 MHz) to which the delay line crystal is resonant. The newly modulated carrier is amplified and then applied to two separate channels. One channel consists of the delay line, carrier amplifier, diode detectors, and video amplifier. The other channel is identical, except that it has no delay line.

A pulse, ready for transmission, is delayed one pulse repetition time so that it can be compared with the returning echo, resulting from transmission of a previously transmitted pulse. The next pulse is delayed for comparison with the third pulse, and so forth. The cancellation network consisting of the two channel circuits functions as a unit. Channel 1 (containing the delay line) accepts the new carrier signal, pulse-modulated by the echo signal. After being delayed by the mercury delay line, this signal is applied to the carrier amplifier. Following amplification, the signal is detected and rectified, and the output appears across a resistive network. Channel 2 (without the delay line) accepts the new carrier signal, pulse-modulated by the transmitter pulse and immediately amplifies the signal. Following amplification, the undelayed signal is detected by a diode that is opposite in polarity to the detector of channel 1, and the carrier frequency is removed. The output signal appears across the same resistive output network as the output from channel 1, and the carrier frequency is removed. The output signal appears across the same resistive output network as the output from channel 1, but with opposite polarity. Thus, the two detector outputs are applied in opposite polarity to the same resistive output load.

The algebraic addition of these two signals provides zero output for a stationary target but yields an output signal for a moving target. The moving target signal is applied to a video amplifier and, following amplification, is applied to a rectifier circuit, because the signal from a moving target is bipolar. The rectified signal is applied to the indicator for display.

FREQUENCY-DOMAIN REFLECTOMETRY (FDR) TEST SETS

Frequency-domain reflectometry (FDR) is a fast, simple, and reliable technique developed to locate defects in microwave cables and wave-guide systems connecting receivers, transmitters, and antennas. Like the time-domain reflectometry (TDR), the FDR tester permits direct readout of cable distance (in feet) to the discontinuity (impedance fault). This system has an impressive record of reliability, greatly reduced service time, and improved service standards. Because the FDR checks cables at their actual operating frequencies, discontinuities outside those frequencies do not affect the test. When measurements indicate a fault, its location (in terms of distance in feet from the point of test) can be precisely determined. Repairs, therefore, can be made quickly and efficiently.

FDR VS TDR

Until the advent of FDR testers, cables were primarily tested by means of TDR (a system that has several limitations). For example, TDR makes measurements covering a spectrum determined by its pulse characteristics and therefore detects all discontinuities, including those outside the operating frequency range, which do not affect a system's operation. With FDR, however, the analysis is made at the actual operating frequency band of the microwave system; thereby assuring proper system performance at the operating frequencies.

The FDR works in waveguides and band-limited systems, including transmission networks that contain filters. The TDR cannot work in such systems because it requires a transmission line that passes the whole spectrum from the fundamental frequency (2 MHz to 5 MHz) to the highest harmonic (15 GHz). Waveguides which act as high-pass filters cannot transmit TDR pulses. Similarly, TDR cannot see through low-pass or band-pass filters because these eliminate the low-frequency harmonics and appear to display a discontinuity on the TDR's CRT.

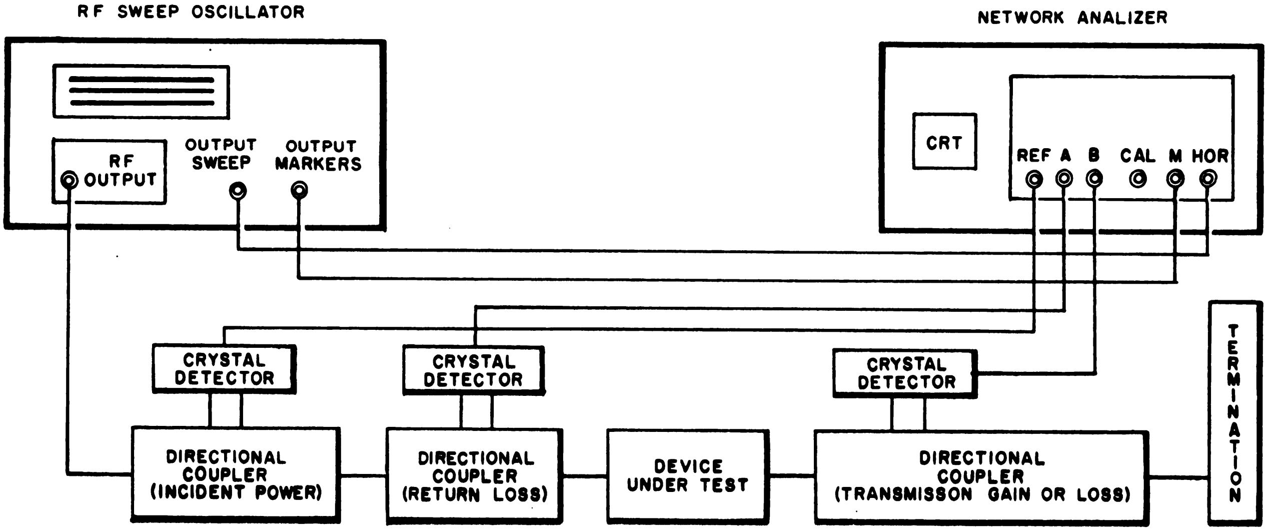


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Figure 2-40.—Typical test setup for VSWR and insertion performance.

FDR TESTING

FDR identifies defective systems by injecting an RF signal into a system and using insertion-loss (attentuation in the line) and return-loss (VSWR) measurements to classify the system under test as good or in need of repair. There are various test setup configurations to measure these losses, based on the particular FDR equipment being used. Figure 2-40 represents a typical test setup for VSWR and insertion-loss monitoring. Such a test configuration provides simultaneous measurement of the losses.

If the input and output connectors of the device under test are accessible, an insertion-loss check verifies input to output performance across the ban. For insertion-loss measurement, the network analyzer (fig. 2-40) (using its B and REF channels) indicates the ratio of output signal to input signal directly in dB. For tests of long cables whose ends are accessible, the FDR allows measurements from a connector end as far as 2,000 feet from the tester. In some systems to be tested, however, either the input or output connector may be inaccessible. For such systems, a return-loss measurement made on the accessible connector will provide a total system check. For return-loss measurements, the network analyzer (using the A and REF channels) indicates (measures) the ratio of reflected power to incident power (output of the RF sweep oscillator unit) directly in dB. As shown in figure 2-40, the signals in each case are sampled via directional couplers.

Comparison of each measured signal with the incident power of the RF oscillator supplies automatic compensation for any swept-source power variations across the band. This gives a true graph of performance in dB versus frequency on the network analyzer CRT. An example of insertion-loss measurement on the network analyzer CRT is shown in figure 2-41. In this example, a loss of less than 10 dB would be acceptable (as determined from previous tests of a good system.) The cable, however, needs repair because a fault (discontinuity) is present, which produces an insertion-loss

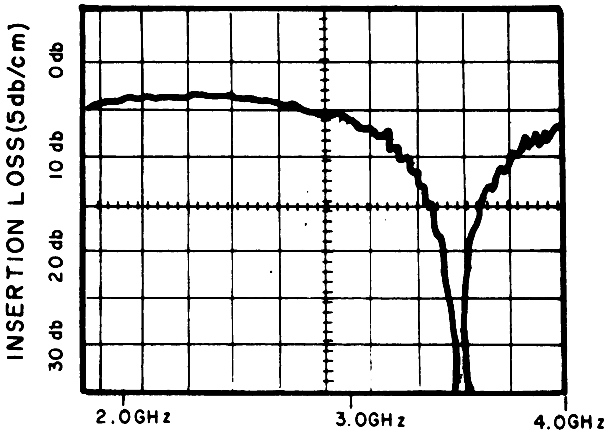

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Figure 2-41.—Insertion-loss display.

greater than 35 dB at a frequency of 3.56 GHz.

An example of a return-loss measurement for the same cable is shown in figure 2-42. Here a loss of 11 dB (as previously determined from a good system), which corresponds to a VSWR of 1.8, would be acceptable. At 3.56 GHz, however, the return loss on the CRT indicates 5 dB, corresponding to a VSWR of 3.6, and is unacceptable.

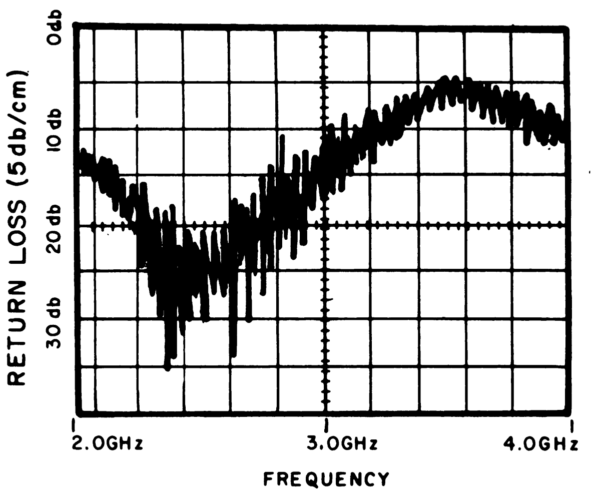

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Figure 2-42.—Return-loss display.

The dual-channel network analyzer in figure 2-40 permits the display of both measurements simultaneously. Both verify the discontinuity in the system cable under test. Single-channel FDR testers require individual test setups for measuring insertion and return losses and comparison of the individual graphs.

Determining Cable Lengths or Distance to Faults

To determine cable length or fault (discontinuity) location measurements, a waveguide or coaxial *tee* is incorporated in the test setup. (See fig. 2-43). The FDR test setup is then calibrated with a calibration cable (provided with FDR set) to establish a known 0-feet reference on the CRT display. Then, the system cable to be tested is connected to the tee. The resultant CRT display of the network analyzer consists of a stationary pattern containing a series of *half-dome ripples.* A count of the total number of these ripples indicates the number of feet from the cable end

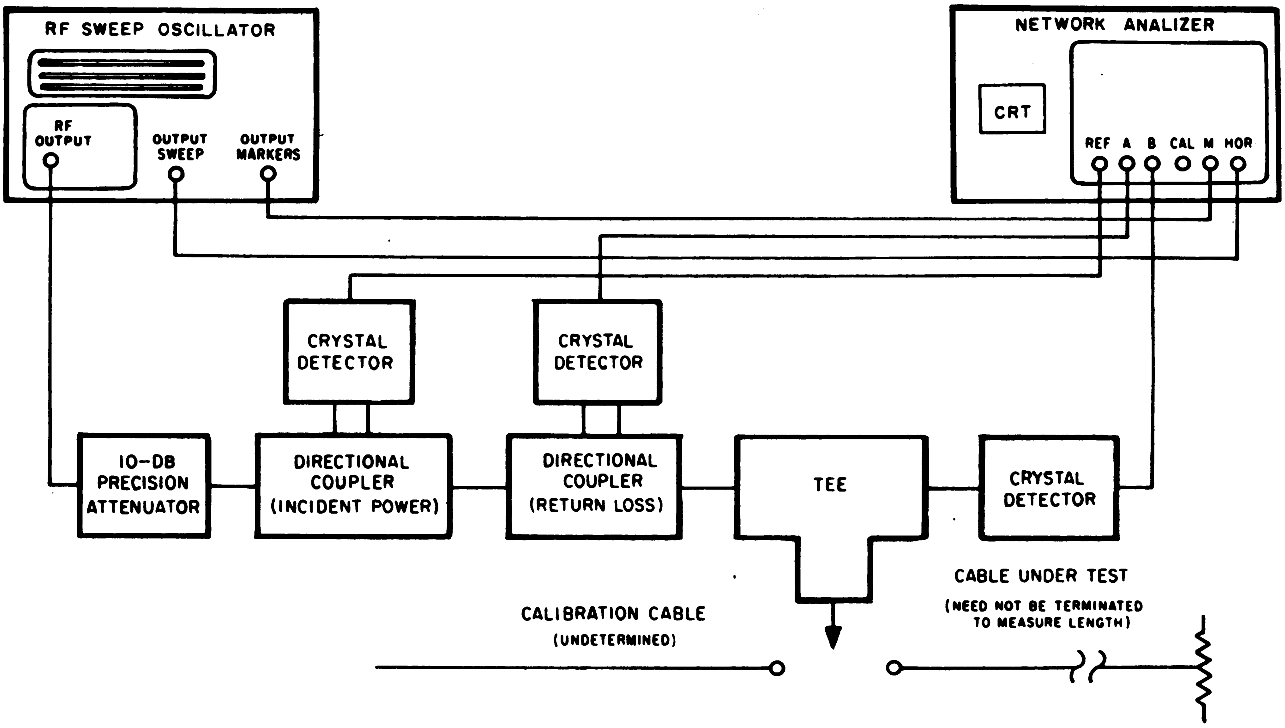

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Figure 2-43.—Test setup for fault-location measurement.

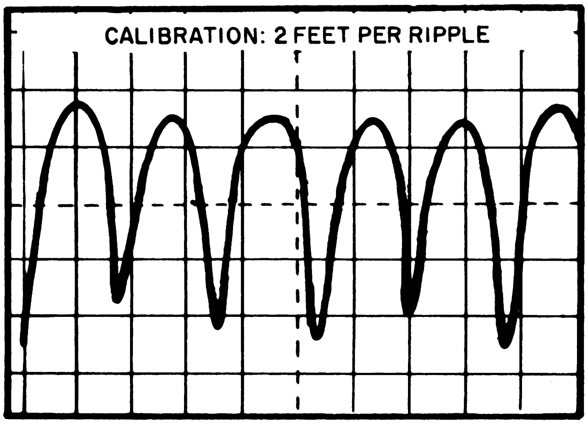

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Figure 2-44.—Measuring a cable fault.

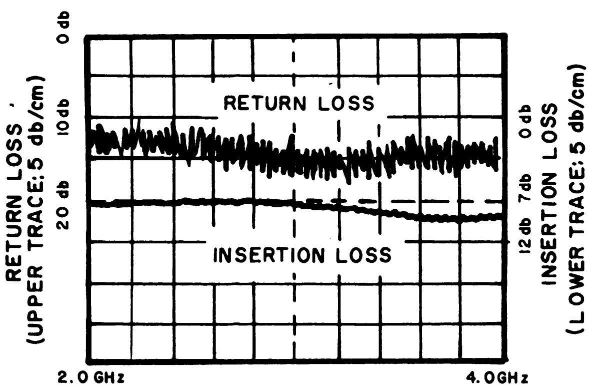

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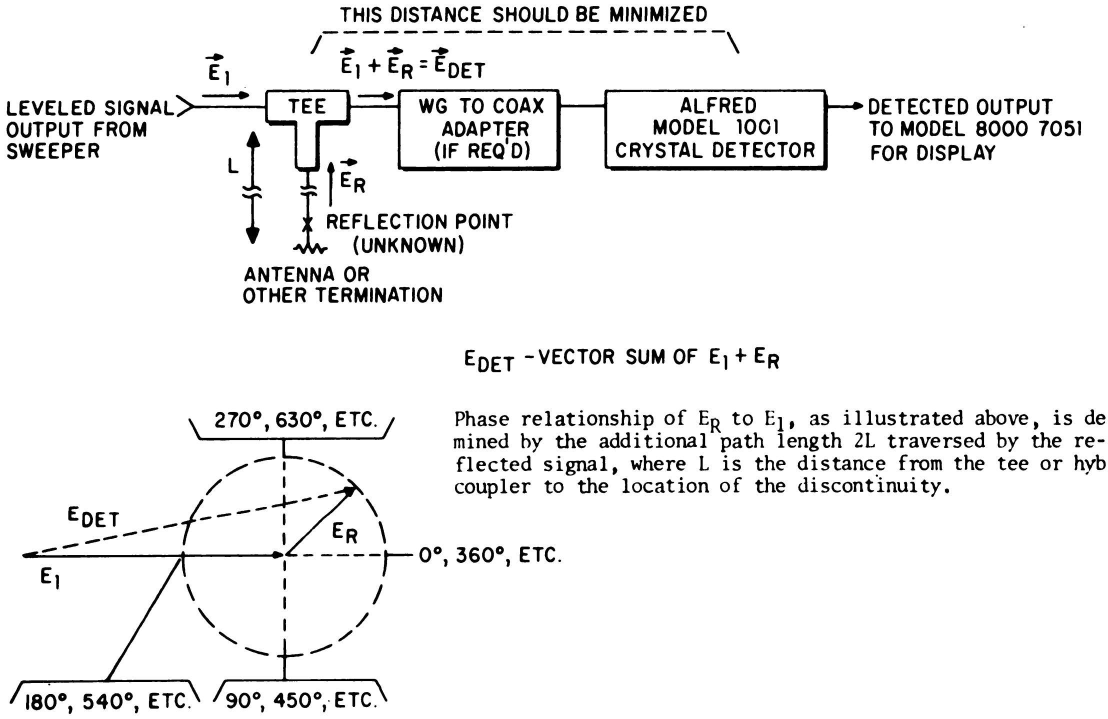
Figure 2-45.—Dual-channel display of a repaired cable.

to the fault (fig. 2-44). The FDR display is from the cable, which needs repairs, shown in figures 2-41 and 2-42. By multiplying the 5 2/3 ripples displayed by the calibration factor of 2-feet per ripple (CRT calibrated that way), you can identify the location of the fault (11 1/3 feet from cable end connector). Figure 2-45 shows a dual-channel display of the cable after the repairs were completed. The insertion-loss is less than 10 dB and the return-loss is greater than 11 dB. This indicates proper performance of the system cable.

Detailed FDR Analysis

With the sweep oscillator output, the transmission system under test, and the crystal detector all connected to the same tee junction, discontinuities and/or termination mismatch in the system reflect some of the incident power. The reflected power combines with the incident signal at the crystal detector. This results in a changing phase relationship that depends upon both distance to the discontinuity and signal frequency. As the frequency is swept, it changes the number of wavelengths which occupy the fixed path from the tee to the point of reflection and back. Thus, the display shows amplitude *ripples* that result from the summing of the incident and reflected signals. This relationship changes with frequency. Figure 2-46 shows how the magnitude of the


THIS DISTANCE SHOULD BE MINIMIZED
$\vec{E}_I$
$\vec{E}_I + \vec{E}_R = \vec{E}_{DET}$
LEVELED SIGNAL OUTPUT FROM SWEEPER
TEE
WG TO COAX ADAPTER (IF REQ'D)
ALFRED MODEL 1001 CRYSTAL DETECTOR
DETECTED OUTPUT TO MODEL 8000 7051 FOR DISPLAY
L
$\vec{E}_R$
REFLECTION POINT (UNKNOWN)
ANTENNA OR OTHER TERMINATION
E_{DET} -VECTOR SUM OF $E_I + E_R$
270°, 630°, ETC.
E_{DET}
E_R
E_I
0°, 360°, ETC.
180°, 540°, ETC.
90°, 450°, ETC.

Phase relationship of E_R to E_I, as illustrated above, is determined by the additional path length 2L traversed by the reflected signal, where L is the distance from the tee or hybrid coupler to the location of the discontinuity.

228.235

Figure 2-46.—Magnitude of the vector sum.

vector sum of these signals, which is the signal level detected for display, varies with frequency.

The resultant display of the varying-magnitude detected signal is actually a logarithmic standing wave ratio (swr) presentation. The ripple peaks are adjacent VSWR maxima which occur (during the sweep) at each frequency in which the *round-trip* length of the reflected wave path from the source to the defect has changed by one wavelength. The number of ripples appearing across the full width of the display (inversely proportional to the frequency separation of adjacent ripples) is a measure of the distance from the discontinuity to the crystal detector. Therefore, direct readout of fault distance is provided when the swept source is operated over a sweep width (ΔF), which is chosen to provide a display calibration (in terms of ripples-per-foot) compatible with the length of the transmission system under test.

In a coaxial system, it can be shown that the distance to a discontinuity, which may be a fault or the cable end, is represented by the equation:

$$D = \frac{492KN}{\Delta F}$$

Where D is the distance to the fault or cable end in feet; 492 is the half wavelength in feet of a 1-MHz wave in free space transmission; K is the propagation constant which relates the propagation velocity in the coaxial system to the

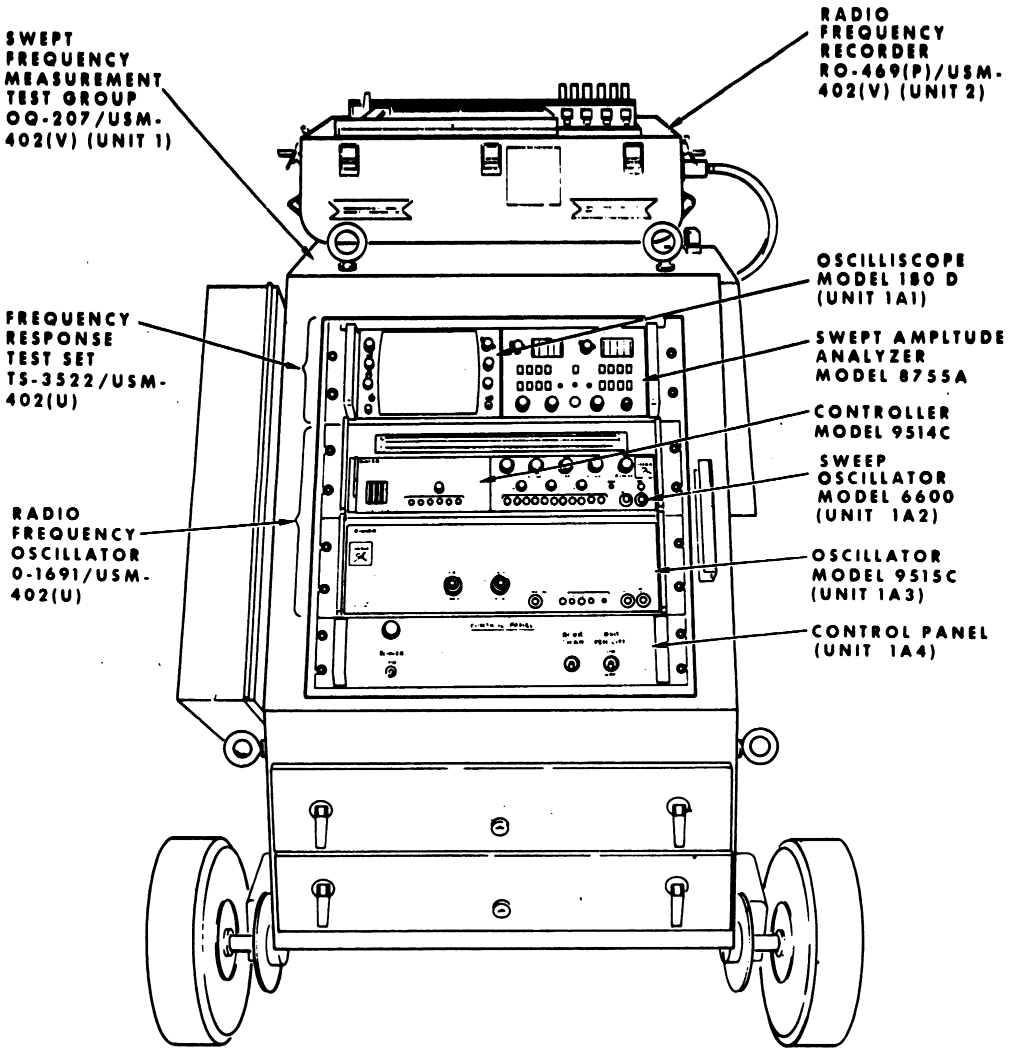

SWEPT FREQUENCY MEASUREMENT TEST GROUP OQ-207/USM-402(V) (UNIT 1)
RADIO FREQUENCY RECORDER RO-469(P)/USM-402(V) (UNIT 2)
FREQUENCY RESPONSE TEST SET TS-3522/USM-402(U)
OSCILLISCOPE MODEL 180 D (UNIT 1A1)
SWEPT AMPLTUDE ANALYZER MODEL 8755A
CONTROLLER MODEL 9514C
SWEEP OSCILLATOR MODEL 6600 (UNIT 1A2)
RADIO FREQUENCY OSCILLATOR O-1691/USM-402(U)
OSCILLATOR MODEL 9515C (UNIT 1A3)
CONTROL PANEL (UNIT 1A4)

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Figure 2-47.—Swept Frequency Measurement Test Set AN/USM-402(V).

velocity in free space; N is the number of ripples observed in the display; and ΔF is the swept-frequency excursion (sweep width) of the signal source in MHz. Note that for any type of cable, ΔF can be selected to equal 492K, so that the distance in feet is equal to the number of ripples (including the fractional ripples) shown in the display. In waveguide systems, the distance down the waveguide to the fault is represented by the same equation, with K showing the relation $\frac{\lambda}{g}$ (λ is the wavelength in free space, g is the wavelength in the waveguide) at the frequency of measurement.

SWEPT FREQUENCY TEST SET AN/USM-402(V)

The AN/USM-402(V) is a portable FDR testing device developed to support the testing of RF transmission lines and devices installed in naval aircraft. It can be used at shore station facilities or aboard aircraft carriers. It can be used to measure and record insertion loss and return loss of units under test and to locate faults (discontinuities) in transmission lines. The tester (fig. 2-47) consists of a three-wheeled cart, a recorder used for recording cartesian coordinate graphs of voltage versus time (see fig. 2-48 and

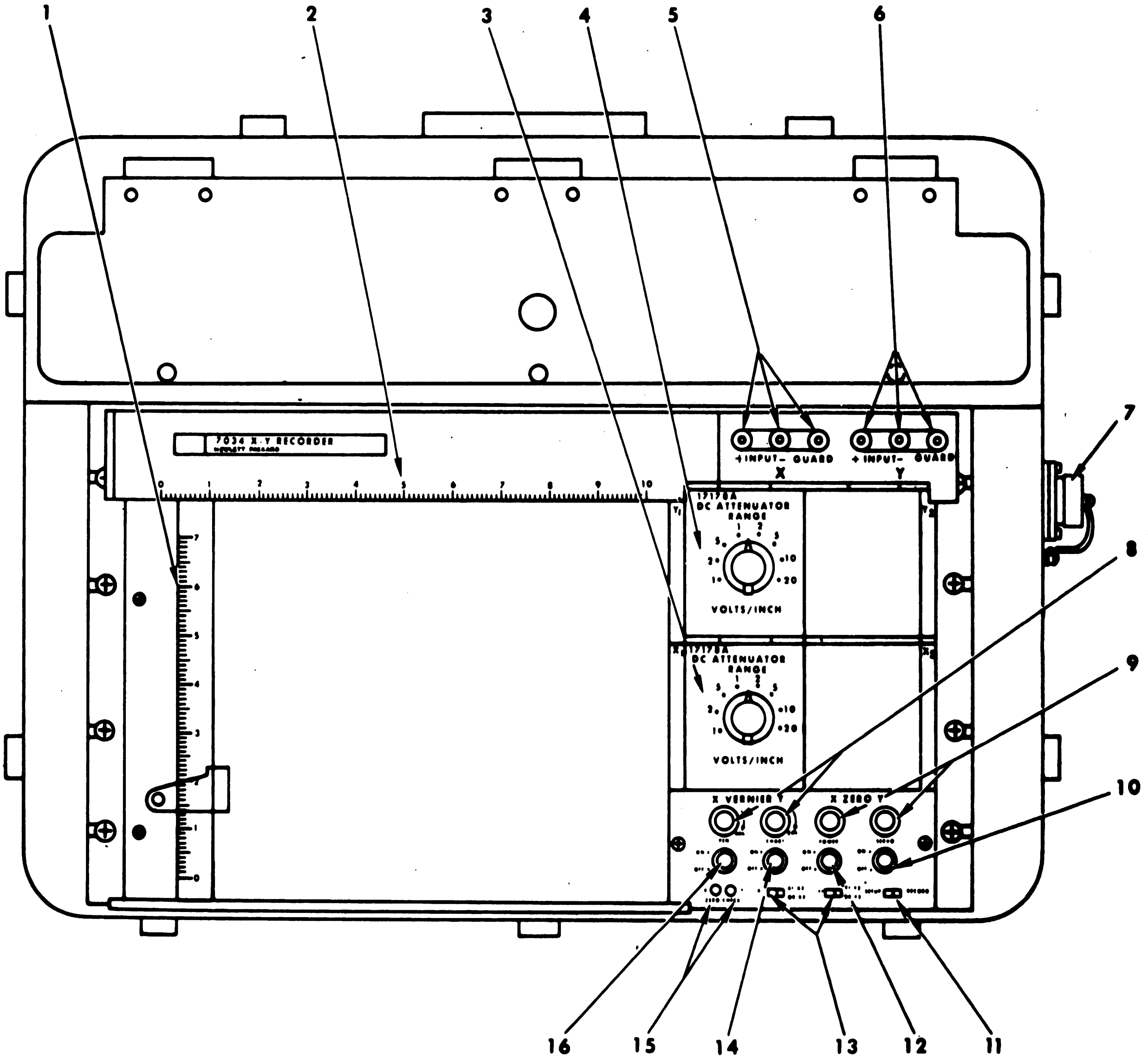

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Figure 2-48.—Radio Frequency Recorder RO-469(P)/USM-402(V) controls and indicators.

Table 2-1.—Radio Frequency Recorder RO-469(P)/USM-402(V) Controls and Indicators

Index No.	Controls and Indicators	Purpose
1	Y Axis Scale	A moveable scale (calibrated in inches) used to determine pen Y position
2	X Axis Scale	A stationary scale (calibrated in inches) used to determine pen X position
3	X_1 Axis DC Attentuator (Unit 2A3)	Model 17178A is a dc attenuator which provides eight ranges from 0.1 V/in to 20 V/in for the X axis
4	Y_1 Axis DC Attenuator (Unit 2A2)	Same as index No. 3 except applies to Y axis
5	X Input Terminals: +INPUT (J101) −INPUT (J102) GUARD (J103)	Three input terminals for the X axis that are connected in parallel to an auxiliary jack (J902) on the rear of the unit. Each terminal is capable of accepting either open wire or banana plug connectors
6	Y Input Terminals: +INPUT (J201) −INPUT (J202) GUARD (J203)	Same as index No. 5 except applies to Y axis
7	Connector 2J1	Unit 2 input connector which normally mates with W3P1. Mates with W4P1 when the recorder is used separately
8	X VERNIER Control (R102) Y VERNIER Control (R202)	A vernier control in each axis for multiplication of input range. Settings from X1 to X2.5. Extreme clockwise position is a calibrated condition (switch actuated). A lock is provided to prevent accidental alteration of setting of each control
9	X ZERO Control (R110) Y ZERO Control (R210)	A control in each axis for controlling pen zero position on the chart. A lock is provided to prevent accidental alteration of this setting
10	SERVO Switch (S601)	A pushbutton switch that controls servo actuation for both axes. When the servos are energized, the switch indicator lamp lights
11	SETUP/RECORD Switch (S602)	SETUP position for making pre-recording adjustments. RECORD position for all other recordings
12	POWER Switch (S901)	A pushbutton that controls application of the AC line voltage to the recorder. When the AC line voltage is applied to the recorder, the switch indicator lamp lights
13	Module Selector Switch: $X_1/X_1 \cdot X_2$ or X_2 (S102) $Y_1/Y_1 \cdot Y_2$ or Y_2 (S202)	The module selector switch in each axis can connect two plug-ins to the main frame. For this model, the switches should remain in the X_1 and Y_1 positions. (Modules must be in X_1 and Y_1 positions to couple signals to the main frame)
14	CHART Switch (S1001)	A pushbutton switch that controls the application of power to the autogrip. When the autogrip is energized, the switch indicator lamp lights
15	X ZERO CHECK Switch (S101) Y ZERO CHECK Switch (S102)	A momentary pushbutton switch in each axis for verifying zero setting of the axis. When the switch is pressed, any input signal to the main frame input is interrupted and the recording pen returns to its quiescent position

table 2-1), a frequency response test set (similar to the network analyzer previously discussed), and a radio-frequency oscillator (similar to the RF sweep oscillator previously discussed.)

The unit operates on either 115-V ac or 230-V ac, 48 to 400 Hz and has an operating frequency range of 10 MHz to 18 GHz. The output of the RF oscillator can be swept or tuned to a single frequency within the band. The operation of this equipment is similar to the typical tester previously discussed. For operating procedures, equipment characteristics, and so forth, refer to NA 17-15LAA-37.1.

REFERENCES

Aviation Electronics Technician 3 & 2, Part 2, NAVEDTRA 10319, Chapter 6

Aviation Fire Control Technician 1 & C, NAVEDTRA 10390-C, Chapter 7

CHAPTER 3

DETECTING AND RANGING SYSTEMS

A laser is a device that produces or amplifies ultraviolet, visible, or infrared radiation. This is done by a process of controlled stimulated emission. The word *laser* is an acronym for light amplification by stimulated emission of radiation. The first lasers were used for surveying because they accurately measured distance. Later, lasers were used by the military. The initial military application of the laser was for fire control. In order to direct gunfire, the range to the target and the direction must be determined. This is done by the laser system. Then, the data gathered by the laser system is used to direct the weapon system. Currently, the technology exists for laser designation of the target for laser-guided munitions. The military laser systems have both range-finding capability for conventional munitions and designation for laser-guided munitions.

In this chapter, you will be introduced to the fundamentals of lasers, cryogenics, and infrared detection. Included is a discussion of the basic operation of laser systems and the safety precautions that you must follow when the systems are used. The specific system that is described in the chapter is the Detecting-Ranging Set AN/AAS-33A. When you complete this chapter, you will be able to do the following:

- Recognize the principles and identify the components of infrared devices
- Recognize the functions and the principles of the FLIR detection set and identify its components
- Recognize the principles and identify the components used in laser devices
- Recognize the functions and operating principles of the laser ranging set
- Identify the advantages and recognize the operating principles of an integrated system

LASER SAFETY

In this section of the chapter, you will learn about the procedures and precautions that should be followed during laser operation so that injury to personnel and damage to material by laser radiation is prevented. The biological and material effects of laser radiation are described, and the descriptions and sources of protective devices are given. Also, safe distances are listed for fielded laser systems, and methods are discussed for estimating the safe distances when safe distances are not listed. Because the Navy uses laser systems, range officers and safety personnel must know laser safety procedures.

LASER SAFETY RESPONSIBILITIES

The safety responsibilities for the various commands and personnel are discussed in the following paragraphs.

Space and Naval Warfare Systems Command

Space and Naval Warfare Systems Command (formerly the Naval Electronics System Command [NAVELEXSYSCOM]) is the lead agency for laser safety in the Navy. It exercises technical direction over laser safety both afloat and ashore. The command is responsible for directing and coordinating the following:

- The establishment of Navy laser safety design standards, documentation, and operational guidance
- Surveys, reviews, and measurements and safety certification of laser target areas, laser systems, and installations
- Reviews of laser systems by the Navy Laser Safety Review Board (LSRB)

- The development of laser protective devices

- An inventory of all military-exempt lasers and Class IIIb and Class IV lasers Navy wide

- The Navy participation in all triservice and interagency laser safety matters and support of the Naval Medical Command (NAVMEDCOM) with regard to laser radiation health medical surveillance

- Support the Chief of Naval Education and Training (CNET) with regard to laser radiation safety training

Naval Medical Command (NAVMEDCOM)

The medical aspects of laser safety are the responsibility of the Naval Medical Command. These responsibilities are as follows:

- Recommend and issue maximum permissible exposure limits
- Establish medical surveillance programs and evaluate suspected laser overexposure limits
- Conduct research on the biological effects of laser radiation
- Provide technical assistance and advice concerning laser radiation health hazards

Commanding Officer

The commanding officer of a ship or naval shore station is responsible for the safety of the personnel under his command. The commanding officer should take action to ensure that personnel performing or supervising laser operations are qualified and certified. Also, the commanding officer should require personnel of other agencies, including contract personnel, to conduct their activities according to safety rules when they are on board a ship or naval shore station. Commanding officers also have the authority to impose and enforce more stringent safety rules than those imposed by higher authority. If no safety rule or regulation exists that applies to a given situation, the commanding officer should submit this requirement to the Space and Naval Warfare Systems Command.

Laser System Safety Officer (LSSO)

Where Class IIIb and Class IV lasers are used, the commanding officer of each activity assigns a laser system safety officer (LSSO). There are many LSSO duties. Some of these duties are as follows:

- Approve, disapprove, or submit to higher authority for safety approval all local laser uses, both portable and fixed, before they are used.

- Establish and issue local laser safety regulations. This duty includes the standard operating procedures (SOP) for safety for indoor and outdoor laser operations.

- Maintain and submit to the Space and Naval Warfare Systems Command all records that are required by SECNAVINST 5100.14a. In addition to a list of military-exempt lasers, maintain a list of all local Class IIIb and Class IV lasers. Submit these lists to the Space and Naval Warfare Systems Command.

- Maintain records on all employees exposed to lasers. Provide medical personnel a list of those personnel that require medical surveillance.

- Investigate local laser radiation accidents and initiate corrective actions. Report any incidents to NAVMEDCOM.

- Survey all local laser installations for safety (at least annually).

- Establish training courses for all personnel that use lasers or laser systems.

- Establish and chair a local laser safety committee. This committee assists the LSSO in the above responsibilities if warranted by the potential hazards of the local operations.

Supervisory Personnel

Laser and laser system supervisors are responsible for normal installation planning, operational procedures, employee training, and accident investigation. These supervisors should maintain a log of all laser firings including the date, time, and location (and any abnormal occurrences related to the firing[s]).

Operating Personnel

All laser operating personnel should understand the potential hazards of laser operations. Also, personnel who operate lasers should be familiar with normal and emergency procedures and personal protective equipment.

LASER CLASSIFICATIONS

Laser classifications have been established to define the hazard level of various lasers.

Class I. Class I lasers or laser systems emit levels of optical energy that are eye safe. Consequently, they require no controls.

Class II and Class IIIa. Class II and Class IIIa lasers and laser systems emit visible CW optical radiation at levels slightly above the maximum permissible exposure (MPE). The normal observer would blink the eye and look away before eye damage could occur. Signs warning personnel about possible hazards should be posted in areas where Class II and Class IIIa lasers or laser systems are being used.

Class IIIb. Class IIIb (medium-power) lasers and laser systems are hazardous to personnel who are within the beampath and viewing the source (intrabeam viewing) directly or by specular reflection. Class IIIb lasers cannot produce diffused reflections.

The principal safety hazard associated with Class IIIb lasers is the reflections off mirrorlike surfaces or when the beam is directed at eye level. When working with these lasers, you should wear the appropriate eye wear.

When small Class I or Class II lasers are coaligned with the higher class of laser, you should wear the eye wear that is appropriate for the higher class of laser. Tools that are used on the laser or optical components should have a dull surface to prevent a specular reflection hazard during maintenance. Safety signs shall be posted outside the shop or laboratory that warn personnel of the hazard involved; or a light warning system may be used to warn personnel of laser operation.

Class IV. Class IV (high-power) lasers and laser systems present eye hazards because of intrabeam viewing and from specular reflections. They may also present hazards if a diffuse reflection is viewed. Also, Class IV lasers present hazards to exposed nonprotected skin or if material is exposed to the beam. Because of the dangers involved, personnel must wear protective eye wear when they are in a room where Class IV lasers are being operated. Door interlocks should be put in all entrances to the shop to remove live power to the laser power supply or to prevent the injection of attenuating material into the beampath. Signs shall be posted as discussed in Class IIIb lasers.

BIOLOGICAL EFFECTS

The electromagnetic spectrum (fig. 3-1) includes radiated energy ranging from gamma rays to dc electricity. The type of energy emitted depends upon the wavelength of the radiation. The optical radiation of the electromagnetic

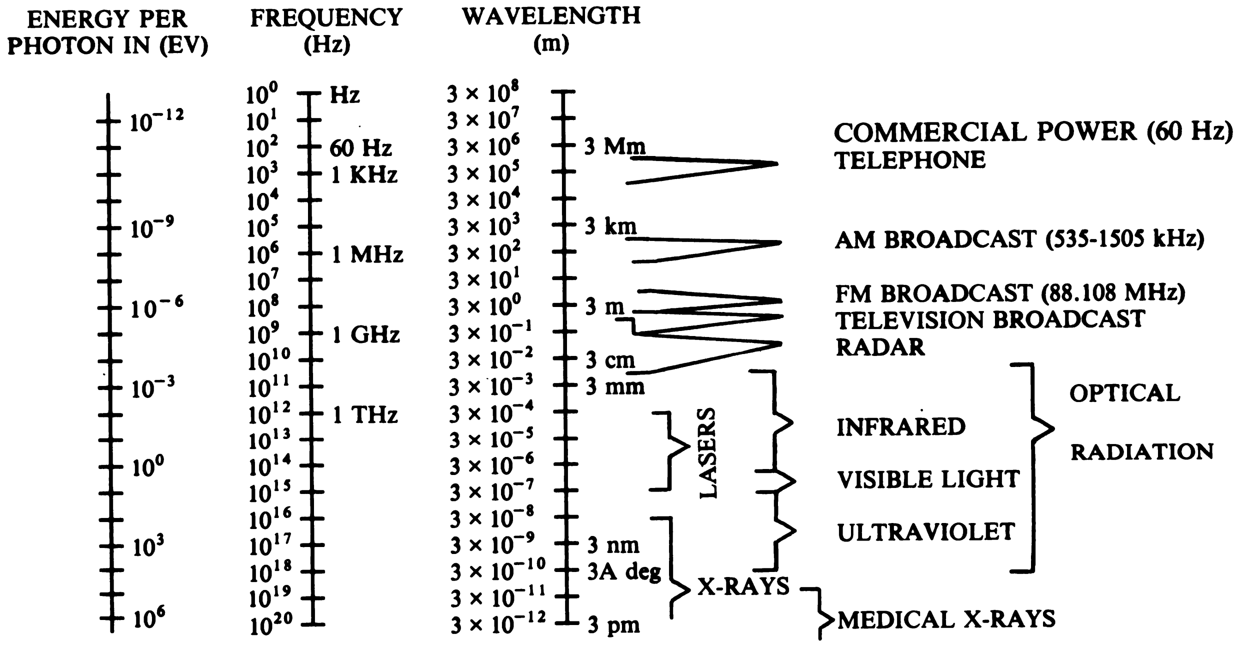

Figure 3-1.—Electromagnetic spectrum.

Table 3-1.—Protection Densities, Devices, and Sources

	Required Optical Densities			Recommended Protection Devices					
	Direct Viewing			Direct Viewing, Air(1)		Direct Viewing, Ground(2)		Optically Aided Viewing(2)	
System	Single Pulse	Multiple Pulse	Optically Aided Viewing	Device	Source	Device	Source	Device	Source
Penguin (Ericson Model UAL 11303)	3.7	4.0	5.0	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGAK-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e
AN/AAS-33A (A6-E TRAM)	3.8	4.6	5.8	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3Filter	e
AN/AAS-37 (OV-10D NOS)	4.5	5.2	5.6	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e
AN/TVQ-2 (GLLD)	3.1	3.9	5.6	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e
AN/AVQ-25 (PAVE TACK)	3.7	4.3	5.8	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e
AN/ASQ-153 (PAVE SPIKE)	3.7	4.2	5.6	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e
AN/PAQ-3 (MULE)	3.3	3.9	5.6	EEK 3/P Visor or EDU 1/P Spectacles	a a, b	LGS-NDGA Goggles or NDGA-7448-1 Spectacles	c, d	4 mm Thick KG-3 Filter	e

NOTES: (1) For protection from single pulse exposure beyond 0.3 km. (2) For protection from multiple pulses at laser output.

a. Aviation Supply Office
Philadelphia, PA 19111

b. Naval Ophthalmological Support and
Training Activity
Yorktown, VA 23691
(Contact activity medical officer)

c. Fred Reed Optical Co.
P. O. Box 1336
Albuquerque, NM 87103
Telephone: (505) 265-3531

d. Glendale Optical Co.
130 Crossways Park Drive
Woodbury, NY 11797
Telephone (516) 921-5800

e. Schott Optical Glass, Inc.
400 York Road
Duryea, PA 18642
Telephone: (717) 457-7485

spectrum includes infrared, visible light, and ultraviolet; it is known as light.

The initial physical effects of laser radiation are thermal, photochemical, or thermal acoustic. The initial physical trauma of exposure is followed by a biological reaction of the tissue itself. The lasting effects of this damage range from complete recovery to severe injury with little or no recovery.

The skin can be damaged by exposure to laser radiation. The large surface area makes it susceptible to radiation exposure; therefore, caution should be taken to protect your skin if you may be exposed to laser radiation. The eye is the one organ of the body that is affected directly by optical radiation because it has no natural protection, and its function is to collect and concentrate light.

General Precautions

Most eye injuries from laser radiation have occurred in the laboratory or intermediate maintenance activity. These injuries usually happen because personnel have not worn the proper eye protection. Control measures must be taken to make sure that personnel use the correct protection for the highest class of laser in operation.

Eye Protection

In any situation where you may be exposed to laser radiation at levels that can cause eye damage, eye protection *must* be worn! To determine when eye protection is required and what type should be selected, you must know the following factors:

- The laser wavelengths
- The maximum intensity of the beam at the eye of the observer
- The maximum permissible exposure (MPE) for that wavelength
- The optical density (OD) required of the filter to reduce the intensity below MPE levels

The characteristics of a protective device that reduce the energy in a laser beam to a safe level for personnel being exposed to the beam is expressed as the optical density (OD) of the device. The following equation is used to figure the OD of a device:

$$OD = \log_{10} (Ii/It)$$

Where Ii is the intensity of the beam, and It is the MPE.

Laser protective devices are available from many sources. Some devices are available through the normal supply channels. Other devices are available from commercial sources only. The recommended protective densities, devices, and their sources for typical laser protective devices currently in the Navy inventory are shown in table 3-1.

PRINCIPLES OF OPTICS AND LASERS

NOTE: Before reading this section, you should review the information on light found in *Avionics Technician 3 & 2*, NAVEDTRA 10319.

The theory of lasers was published around 1956. Along with the theory, a study was reviewed. In the study, methods of extending the range of lasers were looked at using various solids and gases as the method of range extension. It was from this study that laser theory evolved. The first laser was built in 1960 by Hughes Research Laboratories.

A simplified solid-state laser currently used by the military is shown in figure 3-2. The elements

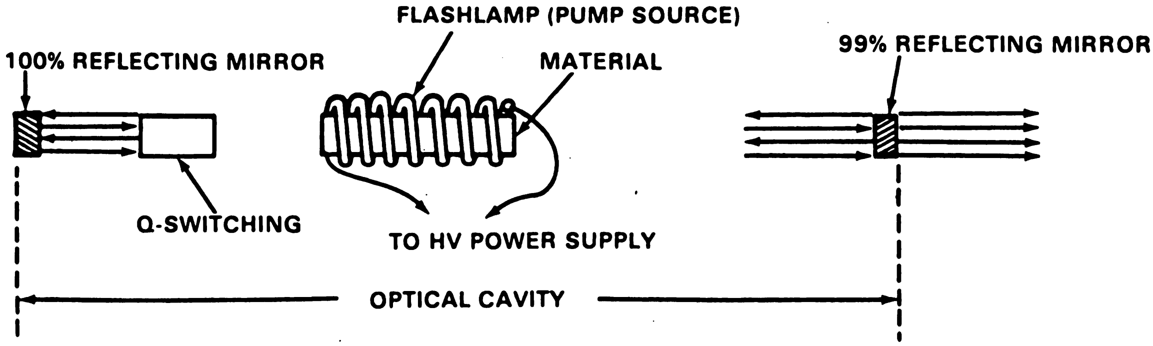

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Figure 3-2.—Typical solid-state laser configuration.

of the laser are the material, pump source, optical cavity (amplifying and modifying the emission), and the output radiation.

The electrons in the atoms of the laser material normally reside in a steady-state lower energy level. When energy is added to the atom, the electron is raised to a higher energy level. The flash lamp (fig. 3-2) is the device used in the solid-state laser to add energy to the atoms. When energy is added to the electrons, they are in an unstable condition. They stay in this condition for a short time and then spontaneously return to their steady-state lower energy level. The transition of the electrons from the higher energy level to the lower energy level releases energy in the form of photons of light. The emitted light rays travel back and forth in the optical cavity through the lasing material between the 100 percent reflecting mirror and the 99 percent reflecting mirror. The photons collide with other excited electrons in the laser material, thereby stimulating the emission of other photons of light. The light energy is amplified in this manner until sufficient energy is built up to be transmitted through the 99 percent reflecting mirror. This action is termed *lasing*. The equipment that accomplishes lasing is the laser.

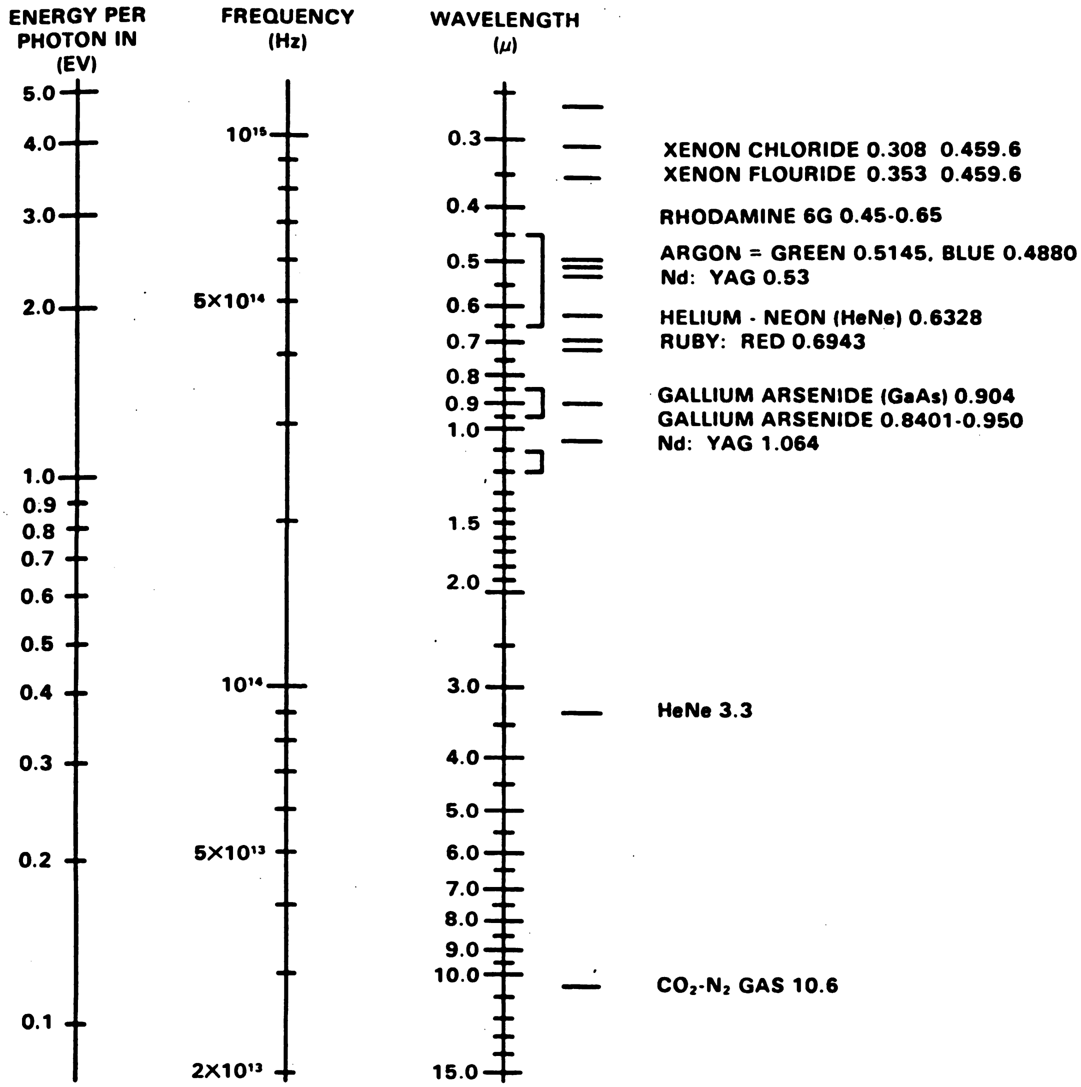

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Figure 3-3.—Laser electromagnetic spectrum.

Find the Q-switch shown in figure 3-2. It is used to provide pulses of extremely short duration. One type of Q-switching is provided by a rotating prism. Only at the point of rotation where there is a clear optical path is light energy allowed to pass. Another type of Q-switching device is a normally opaque electro-optical device such as a Pockels cell. At the time of voltage application, the Pockels cell becomes transparent to light. A complete optical path is formed that allows the transmission of light.

The construction of the gas laser is slightly different from that of the solid-state laser. A glass tube filled with gas is placed in the optical path. This tube replaces the lasing material and flash lamp in the solid-state laser. A voltage (the external energy source) is applied to the tube. The light emitted from this type of laser is normally continuous wave rather than pulsed.

Light from a conventional light source is extremely broadband. It contains wavelengths across the entire electromagnetic spectrum. But, if you place a filter that allows only a very narrow band of wavelengths (such as a red filter) in front of a broadband light source, only red light exits the filter. An analogy can be made between the light from the filter and the light from the laser, with one exception—there is only a single wavelength emitted from the laser.

The wavelength (or color) of light emitted from the laser depends upon the type of material used in the laser. For example, if a Nd:YAG crystal is used as the material in the laser, the laser emits light with a wavelength of 1.064 micrometers. Look at figure 3-3. It shows you some of the types of material that are used for lasing and the wavelengths that are emitted by lasers using these materials. Note that some materials and gases emit more than one wavelength. In these cases, the wavelength of the light emitted depends upon the optical configuration of the laser.

Light from a conventional light source diverges or spreads quite rapidly. If you hold a sheet of paper near a 100-watt light bulb, the entire sheet is illuminated. Figure 3-4 shows the divergence (amount of beam spread) from a conventional light source. On the other hand, laser light has a very narrow beam divergence. If a sheet of paper is held the same distance from the laser as it was from the conventional light source, the laser light has a very narrow beam divergence; it shows a very small point of

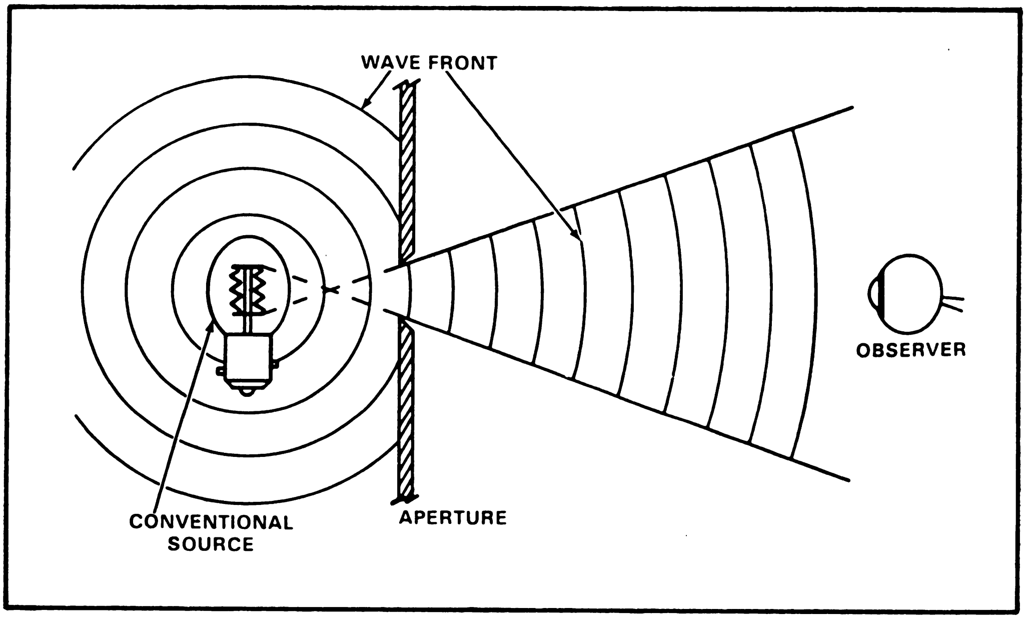

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Figure 3-4.—Divergence of conventional light source.

light (fig. 3-5). The laser light beam has a very narrow beam divergence. For example, if the paper were placed double the distance from the original point, the spot would be twice the size of the one first described. If a paper were held three times the distance, a spot three times the original size would be seen.

TERMS

There are several terms that you may find useful when dealing with lasers. These are watts, joules, irradiance, and radiant energy.

Watts. A watt is a unit of power associated with light energy.

Joule. A joule is a unit of energy. The number of watts being delivered during a short period of time (1 watt a second). For example, a laser capable of delivering 100 millijoules ($1/10 \times 10^{-9}$ seconds) has a power output of 5 megawatts.

NOTE: The output of a continuous-wave (CW) laser is normally given in watts while the output of the pulsed laser is normally given in joules.

Irradiance. Irradiance is the amount of power per unit area. Energy cannot be created or destroyed. In a vacuum, the amount of energy that is available at the output of the laser is the same amount of energy contained within the beam at some point downrange. However, since lasers are not normally used in a vacuum, some energy is lost downrange. Figure 3-6 shows a typical laser beam. The amount of energy available within the sampling area is considerably less than the amount of energy available within the beam. For example, a 0.1-watt laser output might have 0.04 watt measured within a 1-square-centimeter (cm^2) sampling area. In this example, the irradiance is 0.04 watt/cm^2.

Radiant exposure. Radiant exposure is the amount of energy per unit area.

Materials reflect, absorb, or transmit light rays. Reflection of light can be illustrated by using a mirror. If light rays strike a mirror, almost all of the energy incident on the mirror is reflected. Refer to figure 3-7. This figure shows how a plastic or glass surface acts on an incident light ray. The amount of energy transmitted,

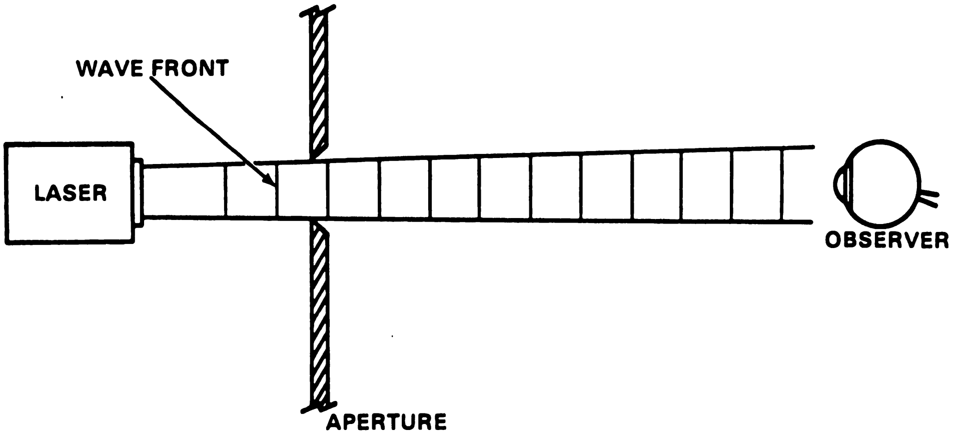

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Figure 3-5.—Divergence of laser source.

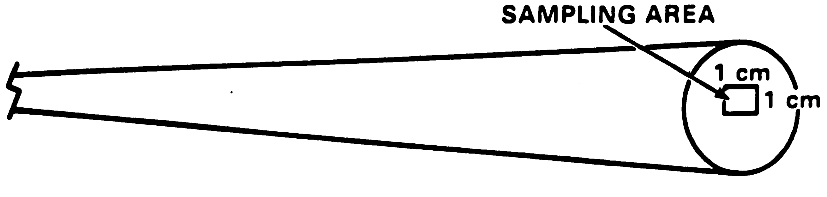

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Figure 3-6.—Illustration of irradiance.

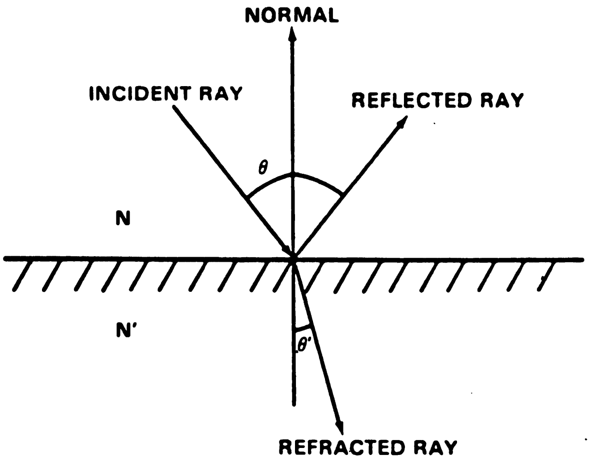

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Figure 3-7.—Light ray incident of glass surface.

absorbed and reflected equals the amount of energy incident upon the surface of the material.

A surface is termed specular when the sizes of surface imperfections and variations are much smaller than the wavelength of the incident optical radiation. A surface is termed diffuse when surface irregularities are randomly oriented and much larger than the incident optical radiation. In the intermediate region of the laser section of the electromagnetic spectrum, it is sometimes necessary to regard the diffuse and specular components separately.

If light is incident upon an interface that separates two transmitting media (such as an air-glass interface), some light is transmitted while some is reflected, and no energy is absorbed at the interface. Since no energy is absorbed at the interface, $T + R = 1.00$; where T and R are the fractions of the incident beam intensity that are transmitted and reflected.

T and R are the transmission and reflection coefficients, respectively. These coefficients depend not only upon the wavelength of the radiation, but they also depend upon the angle of incidence of the beam. The amount of the incident light beam that is reflected and the amount that passes through the material (transmitted) also depends upon the polarization (aligning the light to certain directions) of the light beam.

The angle θ that an incident ray of radiation formed with the normal to the surface determines the angle of refraction and the angle of reflection (the angle of reflection equals the angle of incidence). The relationship between the angle of incidence (θ) and the angle of refraction (θ') is n sine (θ) = n' sine (θ'), where n and n' are the incidence of refraction of the media that the incident and transmitted rays move through, respectively.

A flat specular surface does not change the divergence of the incident light beam significantly. However, a curved surface may change the divergence. The amount of change in the divergence depends upon the curvature of the surface and the beam size incident to the surface. In figure 3-8, the reflection of an incident

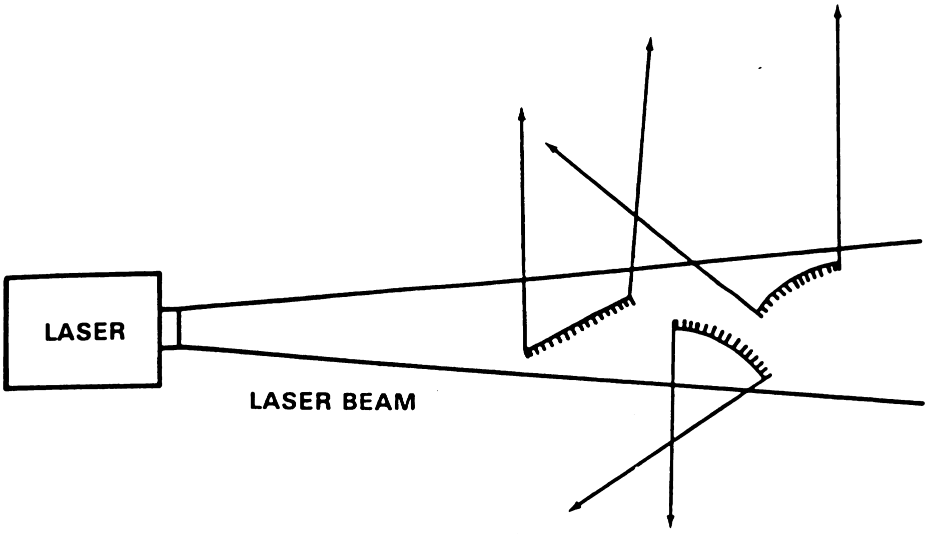

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Figure 3-8.—Specular reflectors.

laser beam is shown on the two surfaces. (The divergence and curvature of the reflector have been exaggerated.) You should note that the value of irradiance measured at a specific range from the reflector is less after reflection from the curved surface than when a beam is reflected from a flat surface.

A diffuse surface is a surface that reflects the incident laser beam in all directions. The beam-path is not maintained when the laser beam strikes it. Whether a surface is a diffuse reflector or a specular reflector depends upon the wavelength of the incident laser beam. A surface would be a diffuse reflector for a visible laser beam, while it might be a specular reflector for an infrared laser beam, such as CO_2. Look at figure 3-9. It shows the effect of different curvatures of diffuse reflectors on incident laser beams.

LASER THEORY

To understand laser and infrared operation, you must understand wave propagation, the component parts of waves, and wave interaction.

Wave Propagation

Wave propagation is the travel of a wave through a medium. Refer to figure 3-10. Here a

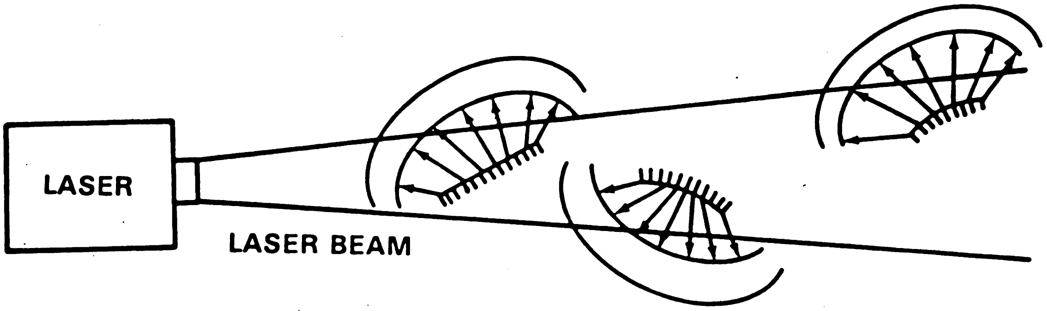

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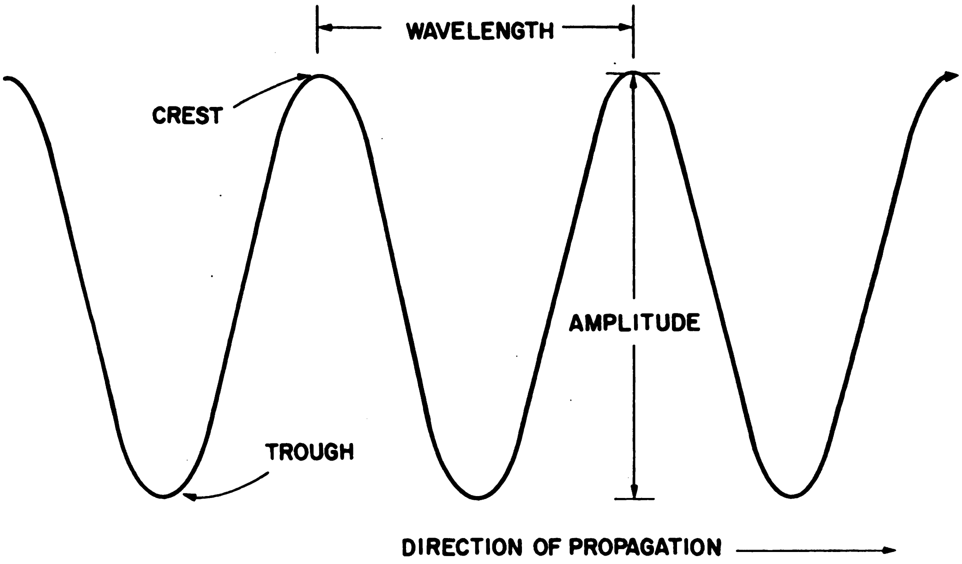
Figure 3-9.—Diffused reflectors.



223.275

Figure 3-10.—Parts of waves.

plain wave is shown, and you can see that the propagation (direction of travel) is perpendicular to the lines of the crest. Another type of wave is a spherical wave that propagates outward like that which a pebble causes when it is thrown into a pond.

Wave Optics

When light strikes an object or a medium, it is either reflected or absorbed. Wave optics involve the reflection or absorption of waves.

REFLECTION.—Refer to figure 3-11. This figure illustrates light reflection and refraction. As an incident wave strikes a reflective surface, it is reflected from the surface. If the reflective surface is smooth, the angle of reflection equals the angle of incidence.

REFRACTION.—Again, refer to figure 3-11. When light passes through a transparent medium, it is *bent* or *refracted*. The term *index of refraction* refers to the amount that the light is bent or the angle of refraction. The higher the index of refraction, the more the light is bent. The index of refraction is a function of wavelength of the incident light. Since different colors have different wavelengths, they have a different index of refraction.

DIFFUSION.—Earlier, you saw how light is reflected when it strikes a smooth surface. When the same type of beam strikes a rough surface, the light is scattered. The term used to describe this scattering is *diffusion*. Diffusion allows you to see nonluminous objects.

Lens Optics

Lenses are used extensively in laser and infrared system operation. Therefore, lens optics must be understood before the system operation can be understood. A *lens* is defined as a piece

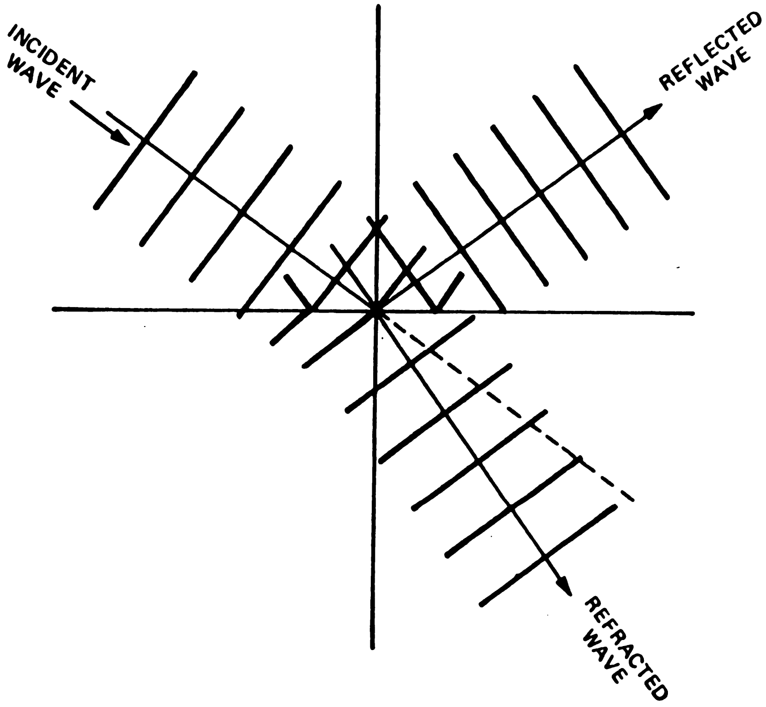


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Figure 3-11.—Reflection and refraction.

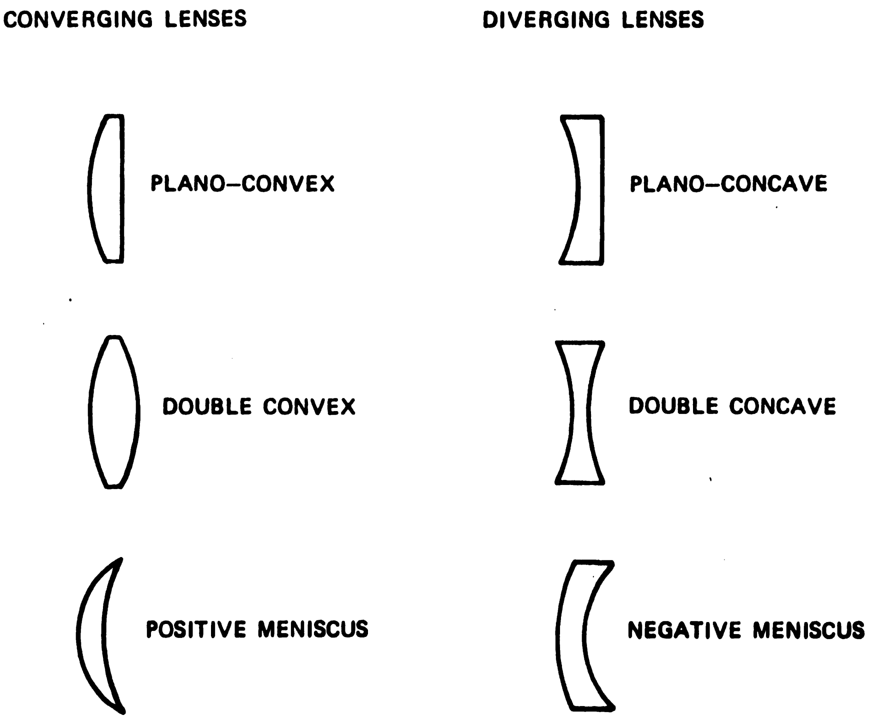

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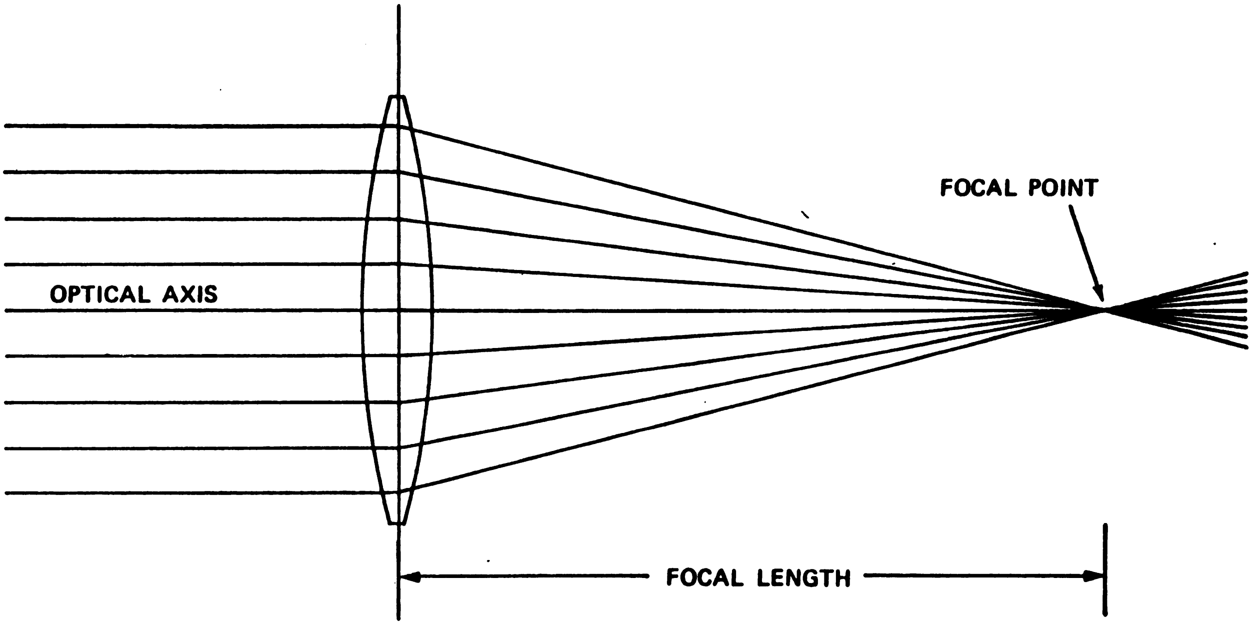
Figure 3-12.—Types of lenses.



223.278

Figure 3-13.—Thin converging lenses.

of transparent material with two opposite refracting surfaces. Converging and diverging lenses are the two categories of lenses. Within these categories, there are three basic types of lenses: convex, concave, and meniscus (fig. 3-12). The converging lenses are thin at the edge and thick in the middie, while the diverging lenses are thick at the edges and thin in the middle.

THIN CONVERGING LENS.—A thin converging lens is shown in figure 3-13. Light rays traveling parallel to the axis of a thin convex lens are refracted so that they converge at a point called the *focal point* of the lens. The distance from the center of the lens to the focal point is the *focal length* of the lens.

THIN DIVERGING LENS.—A thin diverging lens is shown in figure 3-14. In the case of a thin diverging lens, light rays that travel parallel to the axis of the concave lens are refracted so that they diverge at a point known as the *focus*. The distance from the center of the lens to the focus is known as the *focal length*. Since the focus is on the viewing side of the lens, it is considered negative.

Particle Theory of Light

Light, and all other forms of electromagnetic radiation, is energy. Light is composed of particles called photons, which are bundles of massless energy.

PHOTOELECTRIC EFFECT.—In 1887, Heinrich Hertz discovered that metals eject electrons when illuminated. This discovery gave rise to the particle theory of light. The

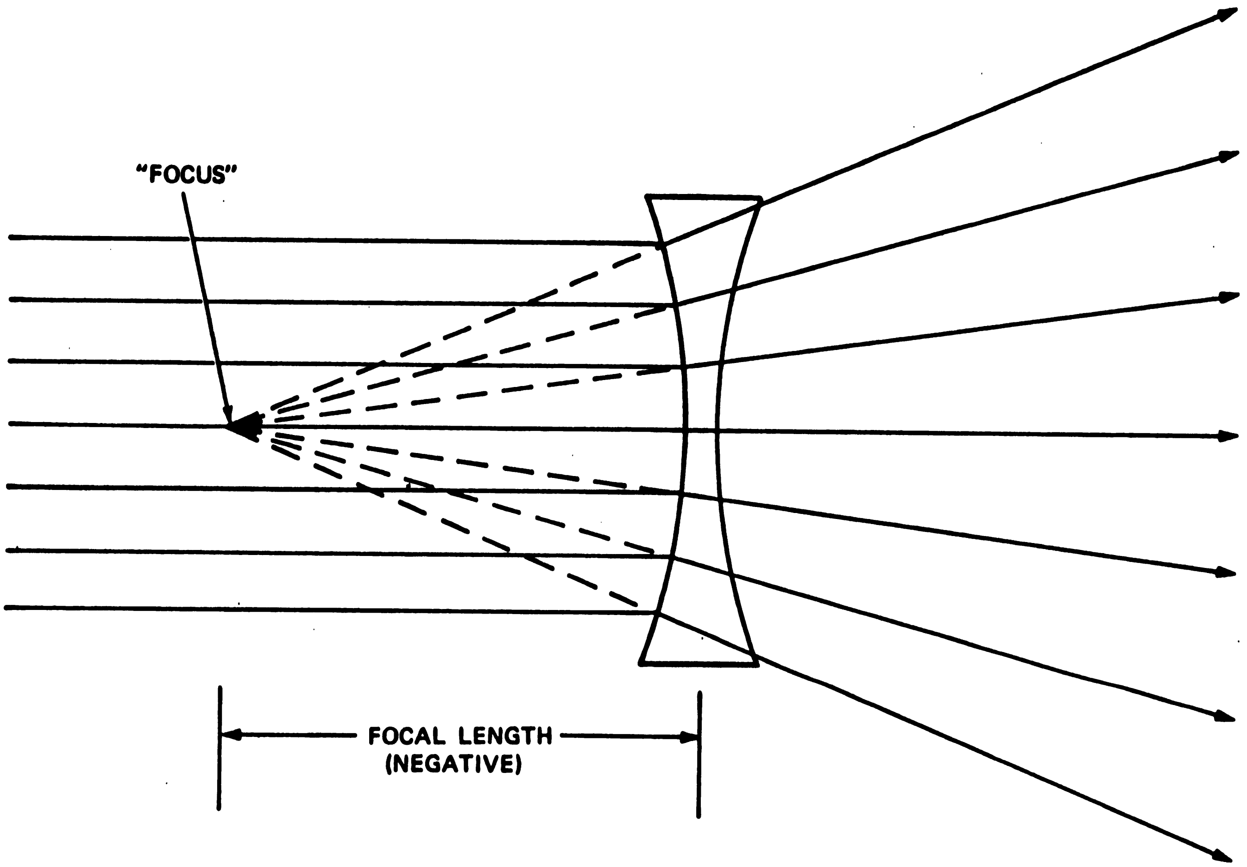


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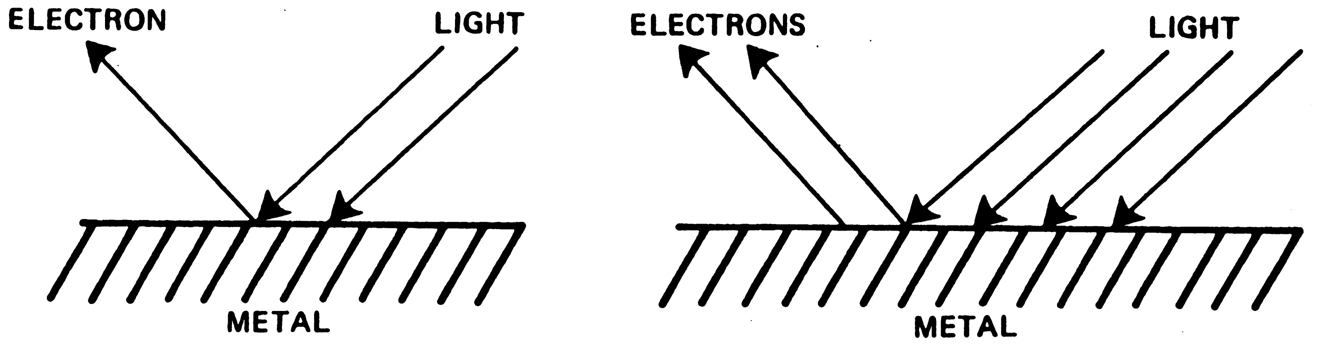
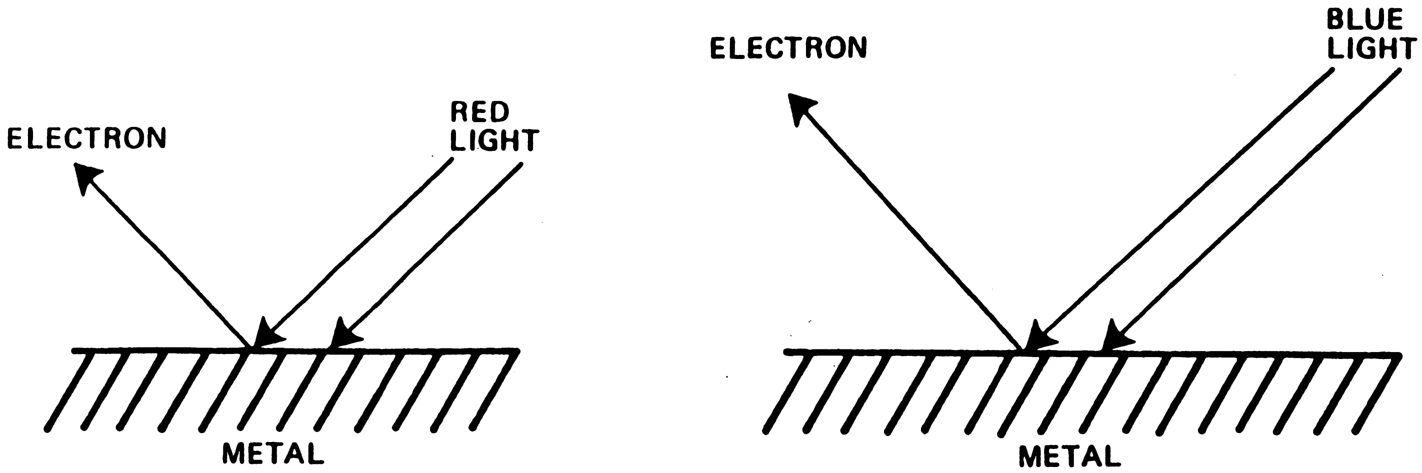
Figure 3-14.—Thin diverging lenses.



INCREASING THE INTENSITY OF THE INCIDENT LIGHT WILL INCREASE THE NUMBER OF ELECTRONS EJECTED.



INCREASING THE ENERGY (INCREASING THE FREQUENCY) OF THE INCIDENT LIGHT INCREASES THE ENERGY WITH WHICH THE ELECTRON IS EJECTED.

223.280

Figure 3-15.—Photoelectric effect.

photoelectric effect is shown in figure 3-15. The following conclusions can be drawn about the nature of light:

- The number of photoelectrons ejected is proportional to the intensity of light; that is, the more intense the light, the greater the number of photoelectrons ejected.
- Maximum kinetic energy (K_{max}) is a function of the frequency of incident light.
- Photoelectrons are ejected instantaneously, regardless of the intensity of the incident light.
- The surface of the specific metal has a threshold frequency; that is, the threshold is the minimum frequency of light that causes photoelectrons to be ejected.

PHOTON THEORY OF LIGHT.—The photon theory of light was announced by Einstein in 1905. This theory explains the photoelectric effect and adds to the understanding of the photoelectric effect in the following ways:

- A beam of light is a stream of photons. The intensity of the beam is proportional to the number of photons in the beam. If one photon knocks out one electron, the photoelectrons will be proportional to the intensity of the beam.
- The energy created in the collision of the photons is transferred instantaneously.

Stimulated Emissions

Lasers operate by stimulated emission. Refer to figure 3-16 while you read this section. An excited atom is struck by a photon. The energy

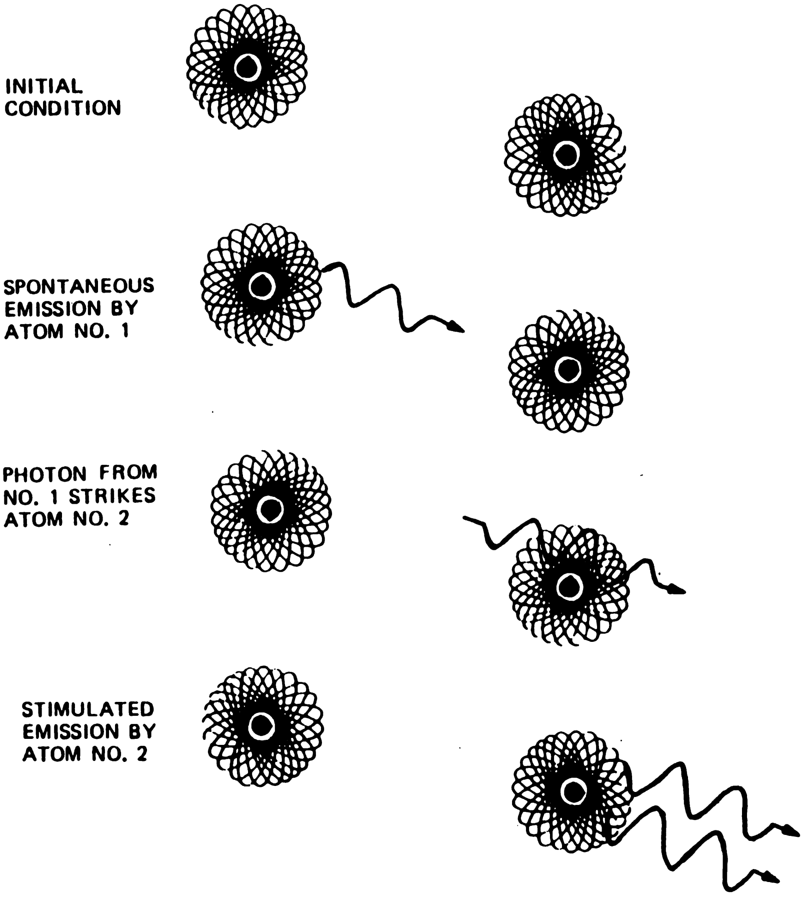
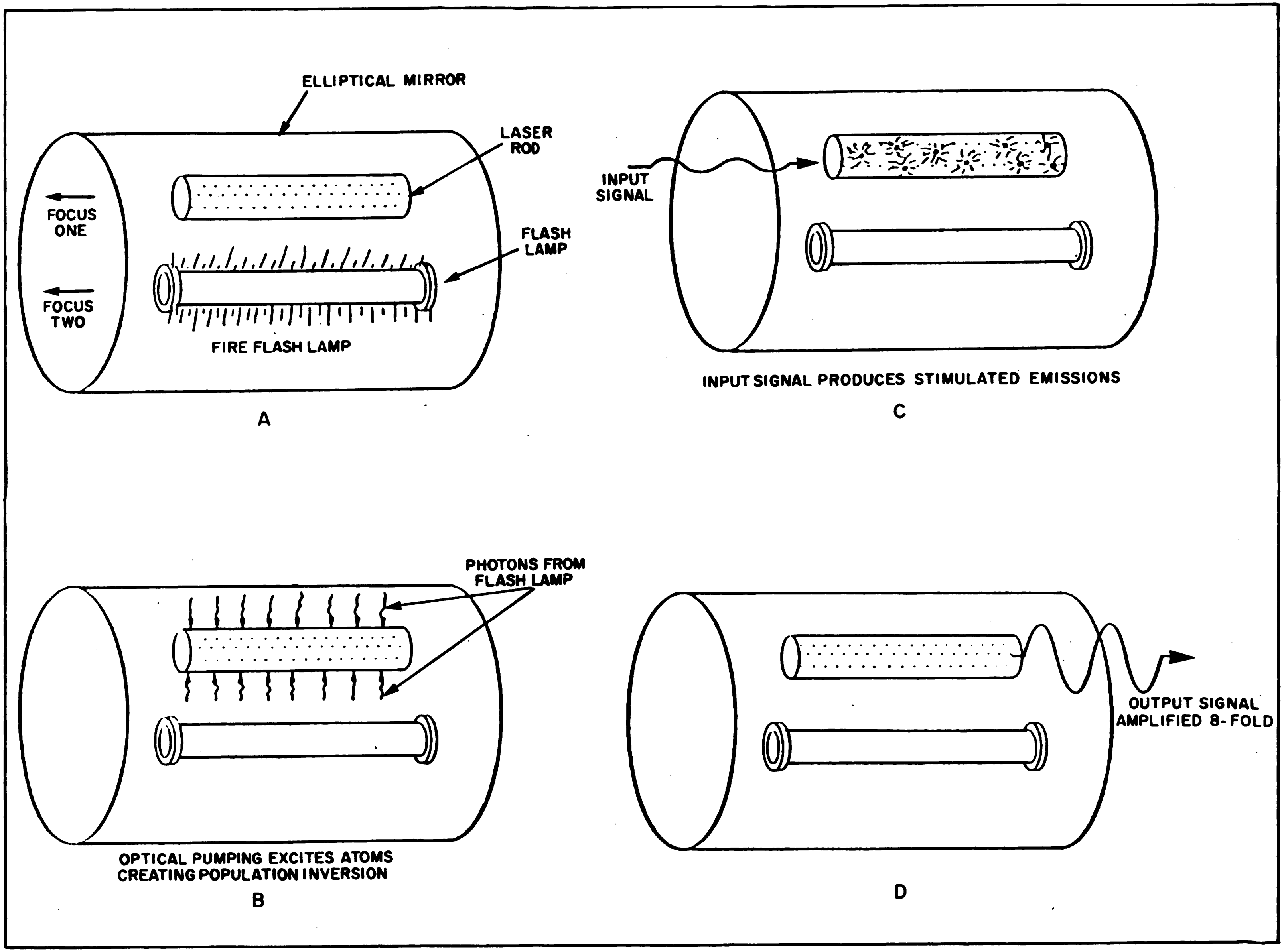

INITIAL CONDITION
SPONTANEOUS EMISSION BY ATOM NO. 1
PHOTON FROM NO. 1 STRIKES ATOM NO. 2
STIMULATED EMISSION BY ATOM NO. 2
223.281

Figure 3-16.—Stimulated emission.


ELLIPTICAL MIRROR
LASER ROD
FOCUS ONE
FOCUS TWO
FLASH LAMP
FIRE FLASH LAMP
A
INPUT SIGNAL
INPUT SIGNAL PRODUCES STIMULATED EMISSIONS
C
PHOTONS FROM FLASH LAMP
OPTICAL PUMPING EXCITES ATOMS CREATING POPULATION INVERSION
B
OUTPUT SIGNAL AMPLIFIED 8-FOLD
D

223.282

Figure 3-17.—Light amplification.

of the incident photon is equal to the transition energy of the excited atom, and the excited atom triggers or stimulates an emission from atom number two. The output produced by the stimulation is emitted instantaneously upon impact, and it is considered an amplified output.

Refer to figure 3-17. The laser rod and the flash lamp are placed at the foci of the elliptical mirror (fig. 3-17, view A). The elliptical mirror can be focused on the laser rod and also the flash lamp. The flash lamp is fixed (fig. 3-17, view B). The photons from the lamp enter the laser tube, causing the tube to go to a high state (excited). The input light signal hits the excited atoms of the laser rod, causing stimulated emissions (fig. 3-17, view C). Finally, the amplified signal leaves the laser tube (fig. 3-17, view D).

Q-Switching

As you can see by looking at figure 3-18, uncontrolled laser output consists of a series of sharp spikes with random heights and random intervals. Normally, this type of output is unusable. Some method of control is needed to regulate or change this output into a single pulse on demand, and quality switching (Q-switching) meets this need.

There are many ways to provide Q-switching, from simple mechanical methods to more elaborate electronic methods. The type of Q-switching discussed in this chapter is the Pockels cell.

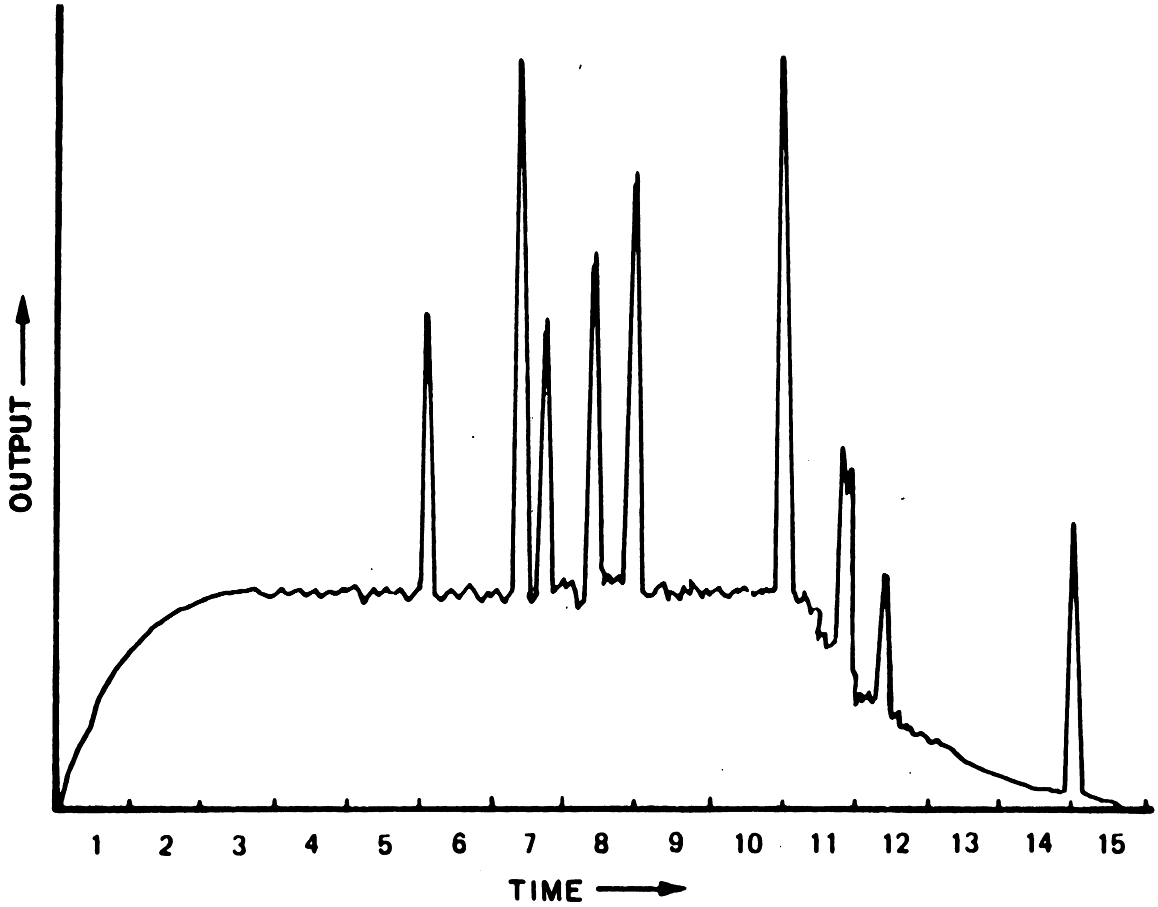


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Figure 3-18.—Typical laser output.

POCKELS CELL.—The Pockels cell is a type of electro-optic Q-switch (fig. 3-19). The Pockels cell is placed between the laser rod and the mirror (fig. 3-19). This cell is composed of lithium niobium ($LiNbO_3$).

POCKELS CELL WITH ZERO VOLTAGE APPLIED.—When light from the laser strikes the first calcite prism, the calcite prism splits the light into ordinary O and extraordinary e beams, which are diverged slightly. These beams strike the second prism where they are bent or diverged again. They leave this prism in parallel and strike a mirror, which reflects them 100 percent. The light stays inside the Pockels cell; thus, there is zero output.

POCKELS CELL WITH 5 KV APPLIED.—Look at figure 3-19, views A and B. Once again, the light from the laser strikes the first calcite prism. Again, it splits and becomes the O beam and e beam. These two beams strike the lithium niobium with the voltage applied, and it becomes birefringent. (Birefringent means to refract the light in different directions.) The outputs from the lithium are the e beam and the O beam, rotated by 90°. This causes the beams to interchange or become each other. The new O beam strikes the second prism where it is refracted sharply to hit the Porro prism, which reflects it sharply back into the optical path to provide the feedback that causes sustained optical oscillations (power buildup). The Pockels cell is the device that allows these oscillations to build until a threshold is reached. Then the laser fires (fig. 3-20).

Solid-State Lasers

The demand for lasers with diverse applications has caused the development of many types of lasers. Most lasers are grouped into five categories; solid state, gas, ion, chemical, and dye. Solid-state lasers were developed first and were most widely used for military applications. For this reason, solid-state lasers are the type discussed in this chapter.

CRYSTALLINE LASERS.—Crystalline lasers are widely used. Two materials are used in these lasers: the matrix substance (*host*) and an impurity (*dopant*). The host is an inert, optically transparent crystalline substance. The

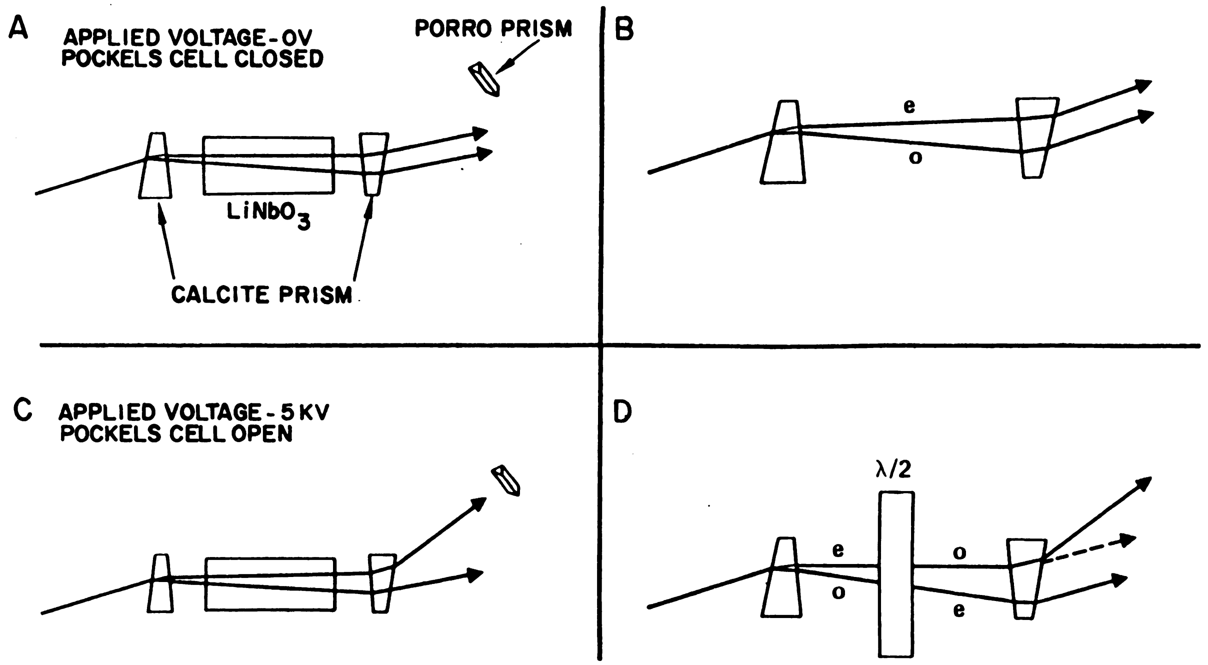

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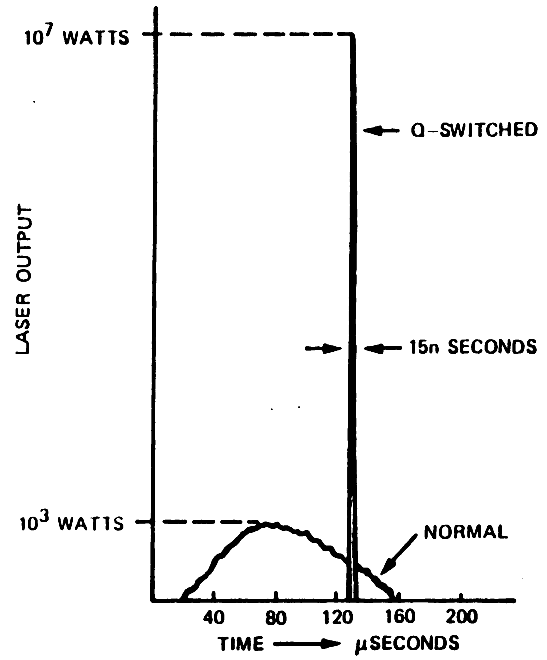
Figure 3-19.—Pockels cell.



COMPARISON OF Q-SWITCHED AND NORMAL (WITHOUT POCKELS CELL) LASER PULSE

- ●Q-SWITCHED
  10 MEGAWATTS (15 NANOSECONDS)
- ●NORMAL
  1 KILOWATT (130 μSECONDS)
- ●TOTAL ENERGY OF EACH PULSE IS EQUAL (AREA OF BOTH PULSES IS THE SAME)
- ●IN EACH CASE, ONE LASER PULSE IS GENERATED FOR EACH "FLASH" OR PULSE OF THE FLASH LAMP

223.285

Figure 3-20.—Laser pulse comparison.

main purpose of the host is to lattice sites (honeycomb arrangement) occupied by the dopant. The substances commonly used as the host include sapphires, yttrium aluminum garnet (YAG), flourite, glass, calcium tungstate, and calcium molybdate. Dopants are ions of rare earth metals, with the exception of chromium. The most commonly used dopants are chromium, neodymium, holmium, erbium, uranium, and samarium.

RUBY LASERS.—The host material for ruby lasers is sapphire crystalline alumina. The dopant is triply ionized chromium, which gives a characteristic red color. Although natural rubies could be used in lasers, their use is rare because large natural rubies with uniform color are rare. Synthetic crystals can be grown to a desired size with no flaws and uniform color.

NEODYMIUM YAG LASER.—Normally, the YAG laser is used as a continuous-wave (CW) laser. The YAG is the host for the trivalent neodymium ion (ND^{+3}) dopant. The neodymium gives the YAG a pale, reddish purple color. The laser rod is produced synthetically, as is the ruby laser. The major difference between the ruby and YAG laser is the output wavelength.

SEMICONDUCTOR DIODE LASERS.—A semiconductor functions somewhere in between a metal (conductor) and a nonmetal (insulator). At high temperatures, the semiconductor has low resistance; while at very low temperatures (near absolute zero), it has extremely high resistance. An example of a semiconductor diode laser is shown in figure 3-21. The semiconductor diode is made by

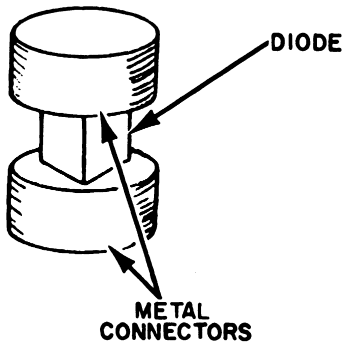


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Figure 3-21.—Diode laser.

sandwiching a diode between two metal conductors that are polished to provide feedback. The semiconductor diode laser has several advantages when compared to other types of lasers.

- They are more efficient.
- They have a wider bandwidth.
- They are faster and do not require Q-switching.

Military Applications

Target designation and range-finding are two of the military applications of lasers.

TARGET DESIGNATION.—Target designation is provided by a laser fixed on a target. A beam is reflected from the target and produces a small, bright spot. Then, a laser-guided bomb, shell, or missile can home in on the spot. To prevent the enemy from jamming the signal, a coded pulse repetition rate is added.

RANGE-FINDING.—When used for range-finding, a laser fires a pulse of light that is pointed at a target. When the pulse is fired, a clock starts. The pulse strikes that target and is reflected. When the returning pulse is detected, the clock stops. Because the speed of light is known, this system is accurate to within 1 foot at a range of 2 miles.

INFRARED IMAGING

The term *infrared* is a Latin word meaning *beyond the red*. Infrared is commonly shortened to IR. The process of detecting or sensing infrared radiation from a target without being in physical contact with that

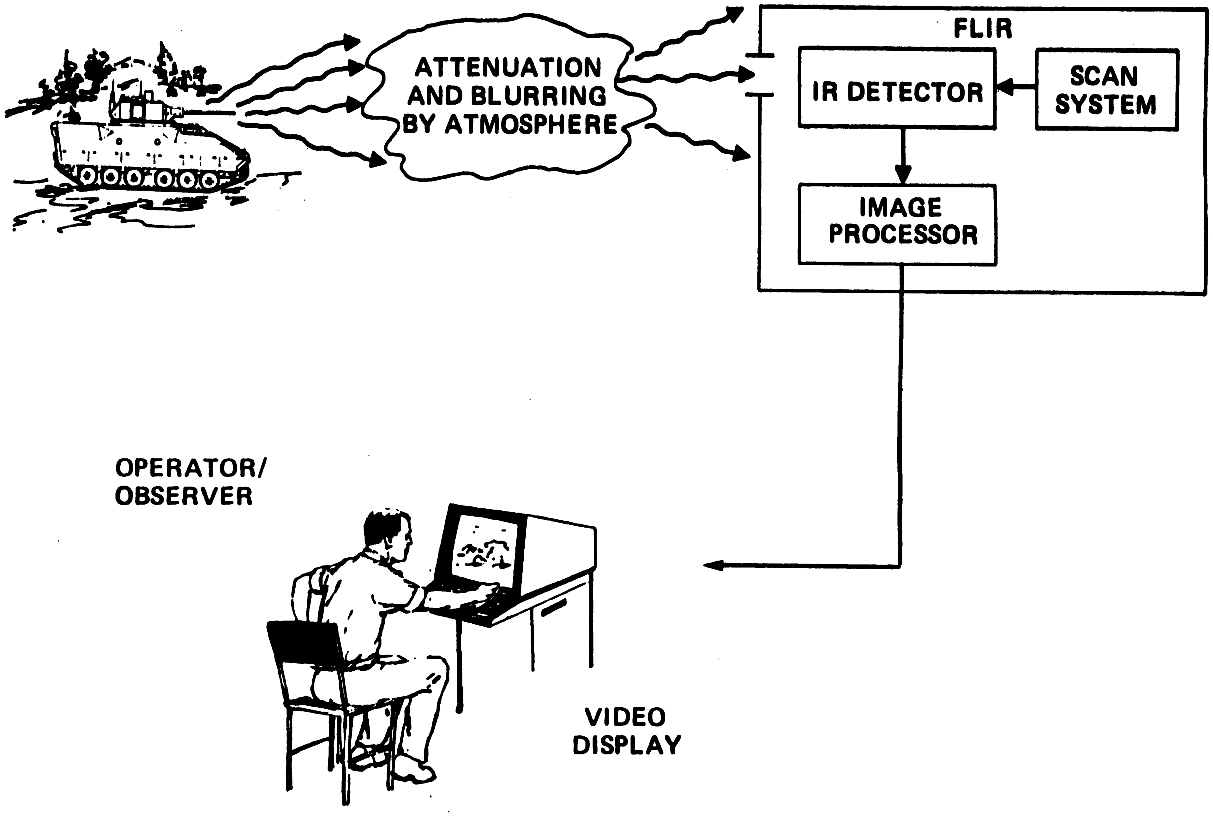

Figure 3-22.—Thermal imaging.

target is known as *remote sensing*. Active and passive systems are used for remote sensing.

Active systems send a signal to the target and receive a return signal. Radar sets are examples of active systems. Passive systems detect a signal or disturbance originating at the target. The signal may be emitted either by the target or another source. Photography using natural light is an example of a passive system.

THERMAL IMAGING

Humans can see only a small part of the entire electromagnetic spectrum; however, other parts of the spectrum contain useful information. The infrared spectrum is a small portion of the entire electromagnetic spectrum.

Infrared radiation is also known as *thermal* or *heat* radiation. Most materials emit radiation in the IR region of the electromagnetic spectrum. In addition to emitting this radiation, objects absorb heat and then reflect it. For example, when an aircraft is parked in the sun on a runway, it gets hotter and hotter. It also radiates more and more IR radiation. The aircraft retains heat after the sun sets and continues to radiate that heat. The presence of an aircraft on a runway can be detected even after the aircraft is moved because the area of the runway that was directly below the aircraft is cooler than the surrounding runway. You can see how the military might use IR radiation.

Thermal imaging is referenced in terms of temperature instead of reflectivity (radar) or color (visible light). Variations of the temperature in a scene tend to correspond to the details that can be visually detected. It is the function of the IR imaging system to process this information and convert it into information that the system operator can use. Currently, the types of imaging systems generally used are mechanical scanning, fast framing devices. They use the frame rate (information update rate) that is similar to television. They are known as forward looking infrared (FLIR) devices.

Before a target can be detected, it must exchange energy with its environment, be self-heating, have emissivity differences, and reflect other sources. Look at figure 3-22. Notice the atmosphere between the target and the FLIR attenuates and blurs the target signal. The FLIR operator aims the limited-field-of-view FLIR to search the scene for targets, using a search pattern and clues, such as radar targets or laser designators.

Thermal sensitivity, image sharpness, spectral response, contrast, and magnification are used in the FLIR system to produce a visual image of the thermal scene. The operator uses training, experience, and image interpretation skills to detect and identify targets.

INFRARED RADIATION

The atmosphere is not a very good transmitter of infrared radiation because of the absorption properties of CO_2, H_2O, and O_3. Infrared radiation is broken into four regions, as you can see by referring to figure 3-23. However, only the first three are discussed in this chapter. Now, look at

NAME		WAVELENGTH (μM)	FREQUENCY (HZ)
NEAR INFRARED	NIR	0.7 μM – 3 μM	$4.3 \times 10^{15} - 1 \times 10^{14}$
MIDDLE INFRARED	MIR	3 μM – 6 μM	$3.0 \times 10^{14} - 5 \times 10^{13}$
FAR INFRARED	FIR	6 μM – 15 μM	$5.0 \times 10^{13} - 2 \times 10^{13}$
EXTREME INFRARED	XIR	15 μM – 1000 μM	$2.0 \times 10^{13} - 3 \times 10^{11}$

223.288

Figure 3-23.—Characteristics of IR radiation.

figure 3-24. This figure shows the transmission spectrum of the atmosphere. You can see that the best transmission is between 3 μm and 5 μm and between 8 μm and 14 μm. The range between these frequencies is known as a window; and infrared imaging devices are designed to operate in one of the two windows, usually the 8 μm and 14 μm.

Infrared Radiation Sources

All matter whose temperature is above −273 °C (absolute zero) emits IR radiation. The amount of the IR radiation emitted is a function of heat. Theoretically, a perfect emitter is a black body with an emissivity of 1. Realistically, the best emissivity is somewhere around .98. The emissivity of various objects is measured on a scale of 0 to 1.

The total energy emitted by an object at all wavelengths is directly dependent upon its temperature. If the temperature of a body is increased 10 times, the IR radiation emitted by the body is increased 10,000 times. If the energy emitted by a black body and its wavelengths is plotted on a graph, a hill-shaped curve results (fig. 3-25). By looking at this graph, you can see that the energy emitted by short wavelengths is low. As the wavelengths get longer, the amount of energy increases up to a peak amount. After the peak is reached, the energy emitted by the body drops off sharply with a further increase in wavelength.

Infrared Optics

Many of the materials commonly used in visible light optics cannot be used in IR imaging systems because, at IR frequencies, these materials are opaque. The optical materials used in IR imaging systems should have a majority of the following qualities:

- Be transparent at the wavelengths on which the system is operating
- Be opaque to other wavelengths
- Have a zero coefficient of thermal expansion to prevent deformation and stress problems in optical components
- Have high surface hardness to prevent scratching the optical surfaces
- Have high mechanical strength to allow the use of thin lenses (high-ratio diameter to thickness)

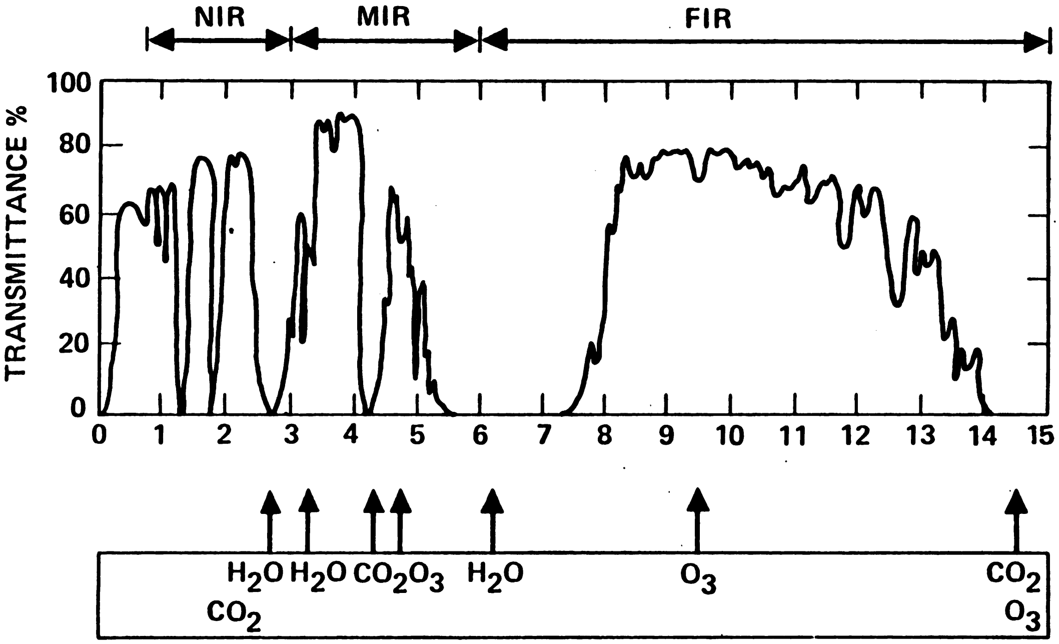

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Figure 3-24.—Transmission spectrum of the atmosphere.

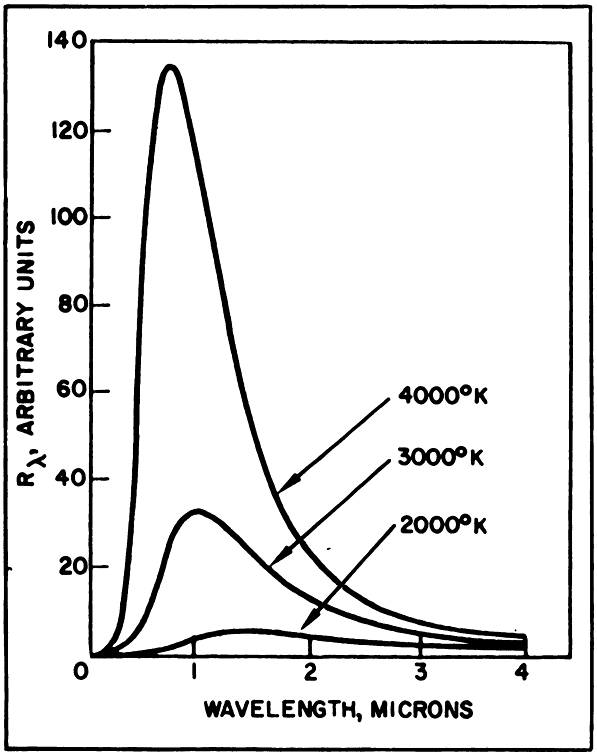

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Figure 3-25.—Blackbody radiation.

- Have low solubility with water to prevent damage to optical components by atmospheric moisture

- Be compatible with antireflection coatings to prevent separation of the coating from the optical component

None of the materials currently used for IR optics have all of these qualities; but silicone, germanium, zinc selenide, zinc sulfide, and IRTRAN have many of them.

Infrared Detectors

The detector is the most important component of the IR imaging system. There are many types of detectors, each having a distinct set of operating characteristics. (Bolometers, Golay cells, mercury-doped germanium, lead sulfide, and phototubes are the most commonly used types of detectors.) Detectors can be characterized by their optical configuration or by the energy-matter interaction process. There are two types of optical configurations—elemental and imaging.

ELEMENTAL DETECTORS.—Elemental detectors average the portion of the image of the outside scene falling on the detector into a single signal. To detect the existence of a signal in the field of view, the detector builds up the picture by sequentially scanning the scene. The elemental detector requires time to develop the image because the entire scene must be scanned.

IMAGING DETECTORS.—Imaging detectors yield the image directly. An imaging detector is considered a myriad of point detectors. Each of the detectors responds to a discrete point on the image. Therefore, the imaging detector produces the entire image instantaneously. A good example of an imaging detector is photographic film.

Energy-Matter Interaction

There are two basic types of energy-matter interaction. They are the thermal effect and the photon effect.

THERMAL EFFECT.—The thermal effect type of energy-matter interaction involves the absorption of radiant energy in the detector. This results in a temperature increase in the detector element. The radiation is detected by monitoring the temperature increase in the detector. Both the elemental and imaging forms of detectors use the thermal effect.

PHOTON EFFECT.—In the photon effect type of energy-matter interaction, the photons of the radiant energy interact directly with the electrons in the detector material. Usually, detectors using the photon effect use semiconductor material. There are three specific types of photon effect detection.

1. Photoconductivity. Photoconductivity is the most widely used photon effect. (See fig. 3-26.)

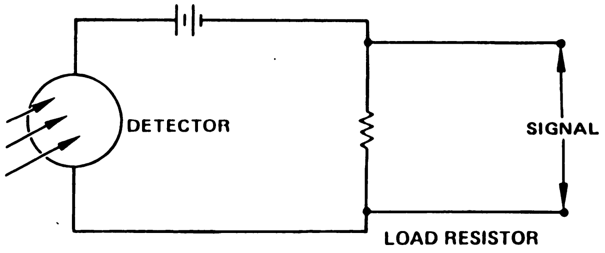

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Figure 3-26.—Photoconductive detector circuit.

Radiant energy changes the electrical conductivity of the detector material. An electrical circuit is used to measure the change in the conductivity.

2. Photoelectric. In the photoelectric effect (fig. 3-27), a potential difference across a PN junction is caused by the radiant signal. The photocurrent (current generated by light) is added to the dark current (current that flows with no radiant input). The total current is proportional to the amount of light that falls on the detector.

3. Photoemissive. The photoemissive effect (fig. 3-28) is also known as the *external photo effect*. The action of the radiation causes the emission of an electron from the surface of the photocathode in the surrounding space. The electron is photoexcited from the Fermi level above the potential barrier at the surface of the metal.

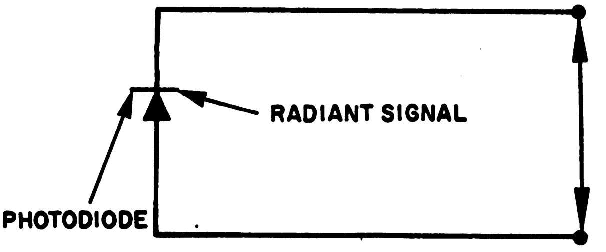

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Figure 3-27.—Photoelectric effect.

Infrared Imaging Systems

The infrared imaging system has the following components: detectors, a scene disection system, front-end optics, a refrigeration system (if required), and an image processing system.

DETECTORS.—Detectors convert the IR radiation signal into an electrical signal that is processed into information used by the operator. Detectors can be arranged in many different configurations for their use in IR imaging systems.

Detector Array.—Only a small portion of the image scene is taken by a detector (or detectors) to achieve maximum resolution. A large number of detector elements can be grouped together to form an array (fig. 3-29, view A). The elements of this array are packed closely together in a regular pattern. Thus, the image of the scene is spread across the array like a picture or a mosaic; each detector element views a small portion of the total scene. The disadvantage of this type of system is that each detector element requires a supporting electronic circuit to process the information that it provides. Also, each detector

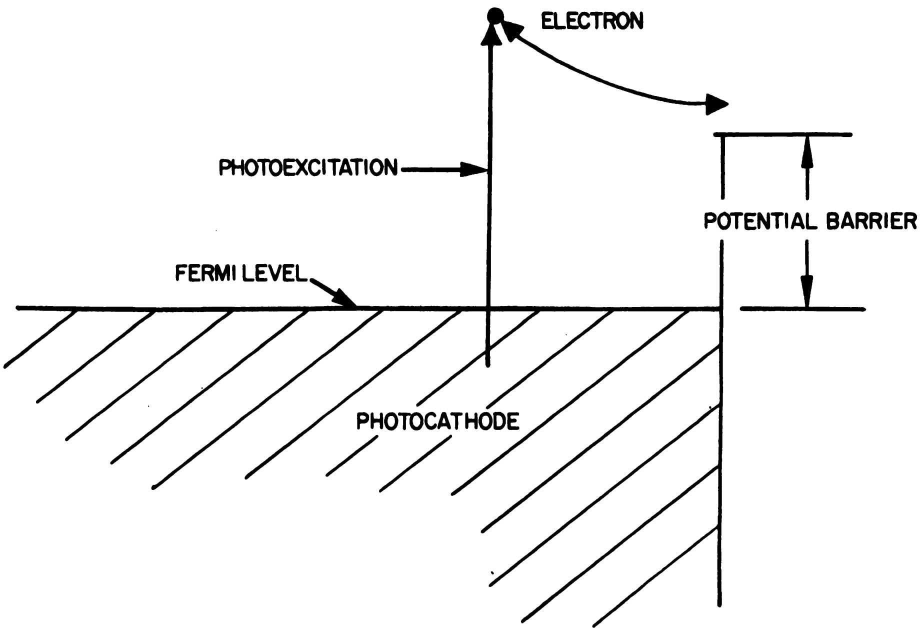

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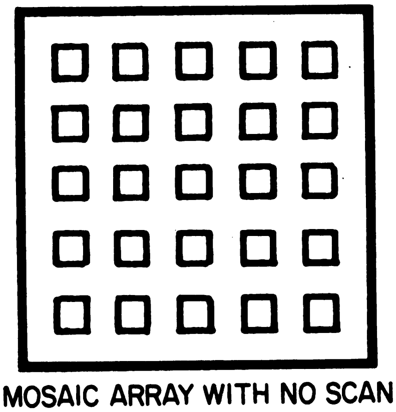
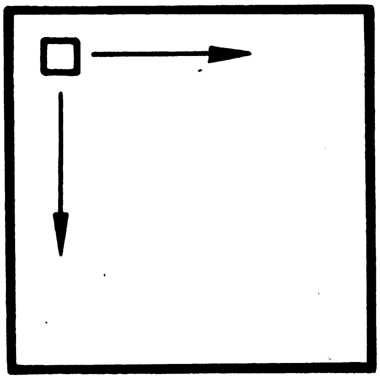
Figure 3-28.—Photoemissive effect.



MOSAIC ARRAY WITH NO SCAN
A



SINGLE DETECTOR WITH VERTICAL
SLOW SCAN AND HORIZONTAL FAST
SCAN
B

223.294

Figure 3-29.—Detector arrays.

element requires a preamplifier to boost the signal to a usable level.

Single Detector.—Another method that is used to provide the operator with information is the single detector (fig. 3-29, view B). Here, there is one detector requiring one set of supporting circuitry. In this type of system, the image is scanned across the detector so that the detector can see the whole image. An optical system is required that can supply the scanning. This type of system is adequate if real-time information is not needed or if the object of interest is stationary or not moving quickly.

SCENE DISECTION SYSTEM.—The scene disection system is used to scan the scene image. There are many types of scanning—one associated with each type of detector array. When a single detector with one axis of fast scan and one axis of slow scan is used, the scene is scanned rapidly in the horizontal direction and slowly in the vertical direction. As a result, the line is scanned horizontally; then the next line is scanned horizontally, and so forth.

A vertical linear array is scanned rapidly in the horizontal direction. One detector element scans one line of the image. In the linear array, there is a space one element wide between each element. The scan is one axis with an interlace being used. A vertical linear array is scanned rapidly in the horizontal direction. After each horizontal scan, the mechanism shifts the image upward or downward one detector element width so that on the next scan, the lines that were missed are covered.

Each system has an optimum configuration of detector array and image disection. If the number of elements in the detector are increased, the system becomes more complicated. The cost of the system is increased, and the reliability of the system is decreased. If the number of detectors is decreased, the amount of information that can be processed is reduced. A compromise between a large number of elements (increased cost) and a smaller number of elements (reduced information) is to use a linear array that is scanned in one direction only. Each detector scans one line of the scene image. The complexity of the electronics is reduced, and the amount of information that is processed is increased. Thus, the size of the scene to be viewed and the detail of the scene is increased.

There are many types of mechanisms that can be used to scan the scene. When scanning using two axes, the two scanning motions must be synchronized. The electronic signal that controls the sampling of the detectors must also be synchronized with the scanning motions.

FRONT END OPTICS.—The front end optics collect the incoming radiant energy and focus the image at the detectors. The optics may be reflective or refractive, or a combination of both. Many systems offer a zoom capability, allowing a continuous change in amplification of the image without changing the focus. Spectral filters are used to restrict the wavelength of light entering the system. This prevents unwanted wavelengths of light from reaching the detector and interfering with the imaging process.

REFRIGERATION SYSTEM.—A refrigeration system is needed in imaging systems because many types of infrared detectors require low temperatures if they are to operate properly. The two types of detector cooling that are used are the open cycle and closed cycle types.

In the open cycle type of cooling, a reservoir of liquified cryogenic gas is provided. The liquid is forced to travel to the detector, where it is allowed to revert to a gas. As it changes from a liquid to a gas, it absorbs a great deal of heat from the surrounding area and the detector.

In the closed cycle type of cooling, the gas is compressed, and the heat generated by the compression is radiated away by the use of a heat exchanger. The gas is then returned to the compressor and the cycle repeats itself.

IMAGE PROCESSING SYSTEMS.—The image processing system is used to convert the data collected by the detectors into a video display. Data from the detectors is multiplexed so that it can be handled by one set of electronics. Then it is processed so that the information coming from the detectors is in the correct order of serial transference to the video display. At this point, any other information that is to be displayed is added.

In other image processing systems, the signals from the detectors are amplified and sent to an LED display or are optically amplified by photomultiplier tubes and projected on a phosphorescent screen.

Infrared Imaging System Configurations

Presently, the Navy uses a direct view parallel scan linear system, the serial scan parallel video two-dimensional array system, and the serial scan standard video system.

DIRECT VIEW PARALLEL SCAN LINEAR SYSTEM.—The direct view parallel scan linear system is shown in figure 3-30. This is the simplest type of infrared imaging system. The scene image enters the system through the infrared lens. Then, it strikes a double-sided scan mirror. The image is scanned across a linear detector array. The signals from the detectors are amplified by the preamplifiers. Then, the signals are sent to the LED drivers, which are arranged in a linear array. Light from the LED array is scanned across the field of view of an ordinary eyepiece by the second side of the scan mirror or on a CRT.

SERIAL SCAN PARALLEL VIDEO TWO-DIMENSIONAL ARRAY SYSTEM.—The serial scan parallel video two-dimensional array system is shown in figure 3-31. A two-dimensional array of detectors is coupled one for one to a similar array of LED. The scan mirror operates in two dimensions. This system offers the same options of direct viewing or CRT viewing as is found in the one-dimensional array.

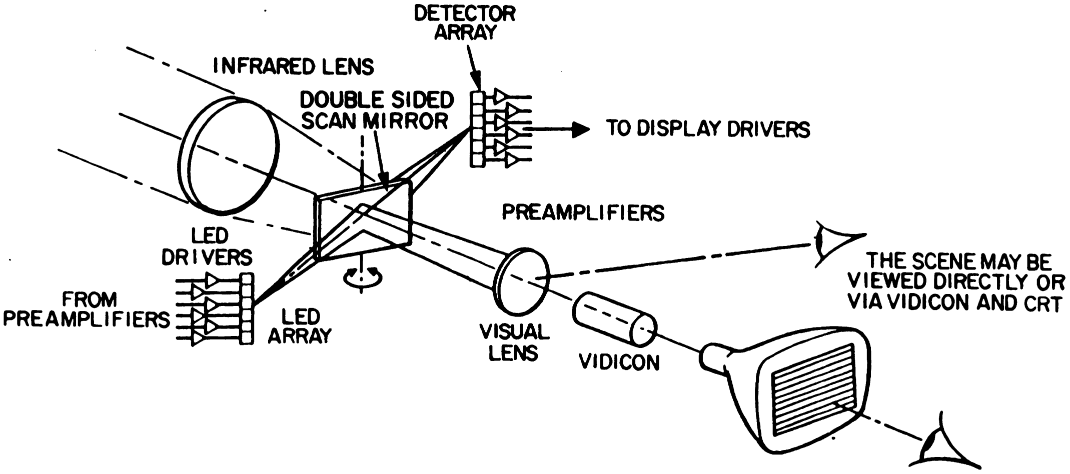


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Figure 3-30.—Direct view parallel scan linear system.

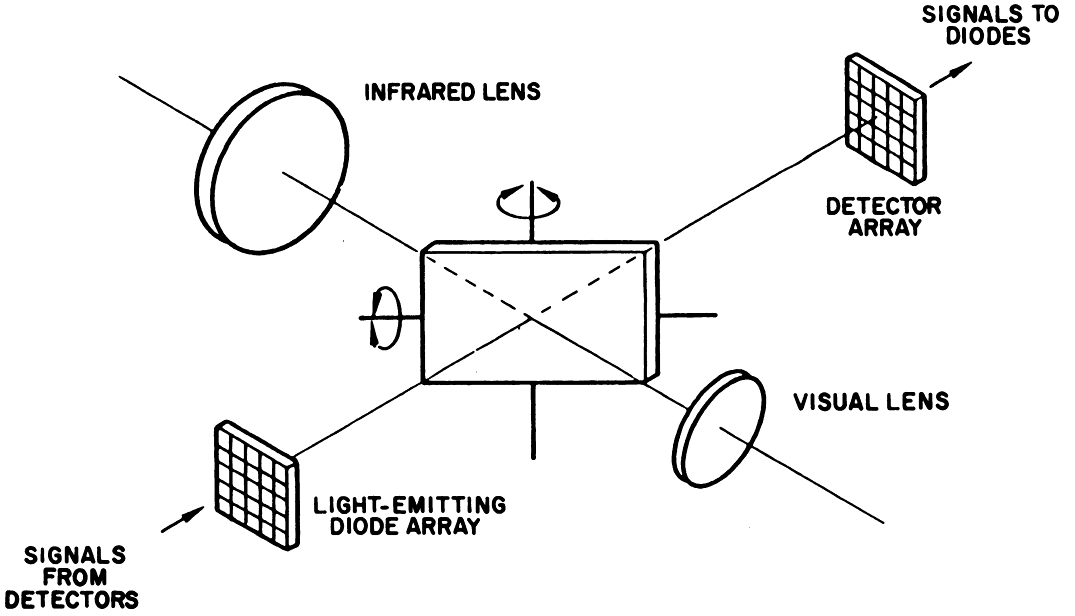

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Figure 3-31.—Serial-scan parallel video system.

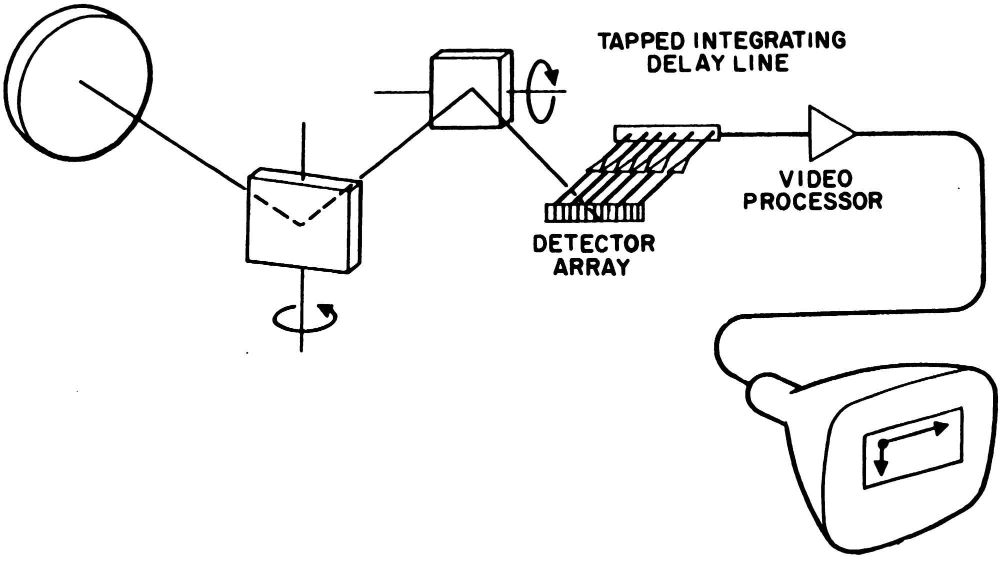

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Figure 3-32.—Serial-scan standard video system.

SERIAL SCAN STANDARD VIDEO SYSTEM.—The serial scan standard video system is shown in figure 3-32. The incoming image is scanned in two dimensions by a scan mirror and an interlace mirror. The interlace mirror shifts the image one detector element width. A linear detector array is used. The information from each detector is amplified by preamplifiers. Then, it is sent to the delay circuitry where the information from the detectors is put into serial form. This circuitry samples each detector at the appropriate time for correct length of time, resulting in a serial output to the video processor.

Elements of a Scanning Infrared Imaging System

The elements of a scanning infrared imaging system are shown in figure 3-33. You should refer to this figure while reading the following section.

The human observer views the system output and interprets the information while operating the controls. The system control interfaces between the operator and system, allowing the operator to control the system.

The stabilization and pointing gimbals provide a stabilized platform from which the imaging system operates. It isolates the system from vibration and sudden motions of the aircraft. Also, it provides a pointing capability for the imaging system.

The collecting optics and filters collect the light (thermal radiation) originating from the target. The unwanted wavelengths of radiation are filtered out through the use of special filters or optical components that transmit only the desired wavelengths. The optical components focus the scene image on the detector array.

The optomechanical scanner scans the scene image across the detector array in a process called *scene disection*. The optomechanical scanner includes a mirror(s) or prism(s) with the mechanical drive controlled by a scan synchronizer.

The scan encoders convert mechanical information about the motion of the scanner to electronic signals, which are used to synchronize the scanner motion with the image generation of the video monitor. This information is sent to the scan synchronizer.

The scan synchronizer controls the motion of the scanner. It interprets with the video process to synchronize the scanner with the display image generation.

The detector assembly contains the detector array that converts the optical signal from the target to an electrical signal. The detector cooler provides cooling for the detector assembly, if required. The detector bias and preamplifier circuits supply voltage or current that is required for the operation of the detectors. They scan the detectors at the appropriate times, and they amplify the signal from the detectors before they are processed further. They also convert the output of the detectors into a serial form.

The video processor converts the detector information into a form that can be presented by the video monitor. It adds additional information for the observer, if needed. The video monitor, usually a CRT, provides information to the operator.

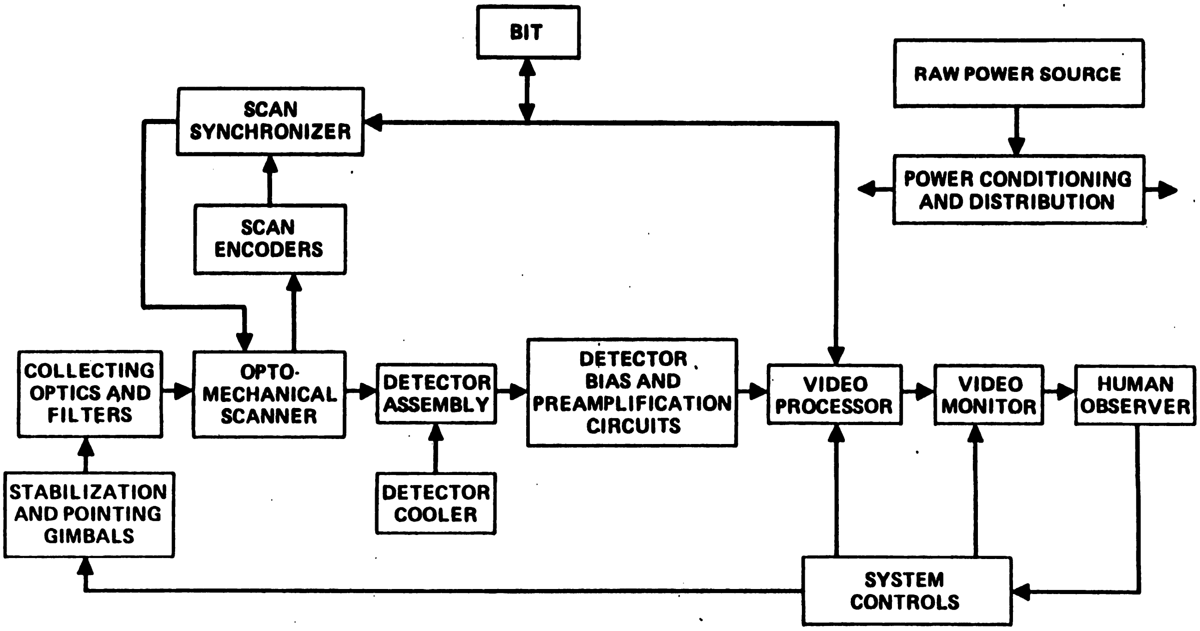

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Figure 3-33.—Flir set block diagram.

The built-in test (BIT) is used to locate and report the nature of failures in the system.

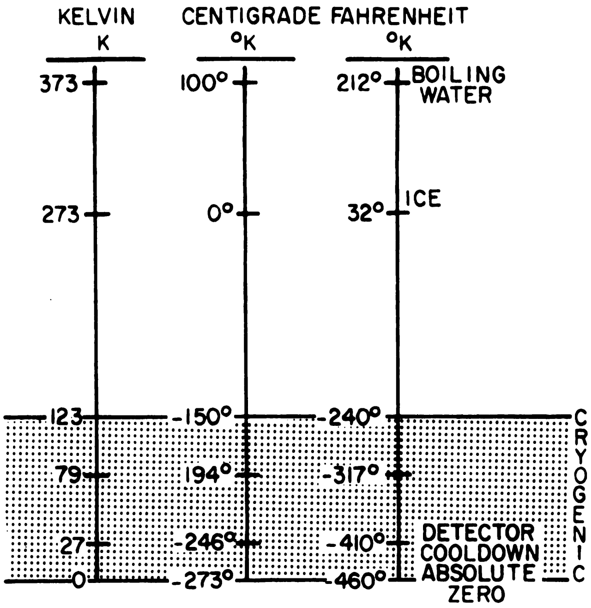

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Figure 3-34.—Absolute temperature scale.

INTRODUCTION TO CRYOGENICS

Cryogenics is the science that involves the study of very low temperatures. The word *cryogenic* comes from the Greek root *cryo* or *kyros*, which means icy cold or relating to the cold.

Cryogenic temperatures extend from − 150 °C downward to − 273 °C (absolute zero). Under such extreme temperatures, many metals become brittle and shatter, atmospheric gases turn into liquids, electrical resistance disappears in some materials and current flows indefinitely without loss (super conductivity).

Heat is a form of energy, and cold is the absence of heat. When a system cools, heat flows out of the system. Therefore, cold can be viewed as a physical manifestation of a lack of energy. The temperatures of a system are an internal feature of the system; therefore, cold is related to a low internal energy of a system.

Why study cryogenics? Many modern systems require cryogenic temperatures to operate properly, imaging systems being one of these. The detectors of the imaging system require cooling for maximum efficiency. Some sort of refrigeration system is needed to provide these low temperatures. If you are to understand the operation of a refrigeration system, you must understand thermodynamics. But, before you begin the following section, you should refer to figure 3-34. This figure illustrates a numerical scale by which degrees of hot and cold may be measured.

When bodies at different temperatures are brought together in thermal contact, heat flows from the body at the higher temperature to the body at the lower temperature. The flow of heat stops when the two bodies are at the same temperature (thermal equilibrium).

IDEAL GAS LAW

Nearly all thermodynamic systems have a working fluid of some type. A theoretical fluid (gas, depending upon temperature) is used to explain the ideal gas law, and this fluid is known as an *ideal gas*. The following assumptions can be made about the nature of this ideal gas:

- The molecules that make up ideal gas are very hard, small spheres whose volume may be neglected when compared to the volume of the gas as a whole.
- The molecules do not interact with each other, only with the walls of the container; they do so by elastic collision (a molecule leaves the wall at the same speed it was traveling before the collision).

Real gas behaves in a manner similar to that of ideal gas, especially at low pressures. However, real gas differs from ideal gas in the following ways: the molecules of a real gas are large enough that their volume must be accounted for when calculating gas volumes, and the molecules do collide with each other.

ENERGY

Energy is the driving force of the universe. The following assumptions can be made about energy:

- Energy is the fuel required to make things happen.

- No system may operate without a transfer of energy.

- Heat is a form of energy.

- A system has an internal energy (the sum of all potential and kinetic energies of the system or molecules of a gas).

- In a closed system, energy is conserved, although it may change states (potential to kinetic).

ENERGY AND THE IDEAL GAS

In the ideal gas, energy is in the form of kinetic energy of the molecules. When the internal energy of the gas is increased, the molecules move faster; they have a high kinetic energy. If the mass of the molecules is low, the molecules move faster. Therefore, the higher the temperature of the ideal gas, the higher its internal energy and the faster the molecules move.

Molecular motion (movement of molecules within a mass) also produces the phenomenon of pressure. As the molecules move about a container, they collide with the walls, exerting a force on the walls. The hotter the gas, the faster the molecules collide with the walls, thus, the higher the pressure.

PHASE CHANGES

Matter exists in three states: gas, liquid, and solid. For matter to change from a solid to a liquid or from a liquid to a gas, it must absorb a great deal of energy. The reverse is true. The process by which a solid changes to a liquid is known as *fusion*, and the process by which a liquid changes to a gas is known as *vaporization*. This process is a good vehicle for heat transfer. It is the basic theory behind refrigeration.

LAWS OF THERMODYNAMICS

The four laws contained in this section deal with thermodynamics. They are basic to the theory of refrigeration and cryogenic systems.

1. *The Zeorth law of thermodynamics states that when two systems of the same temperature are placed in thermal contact no heat will flow.*

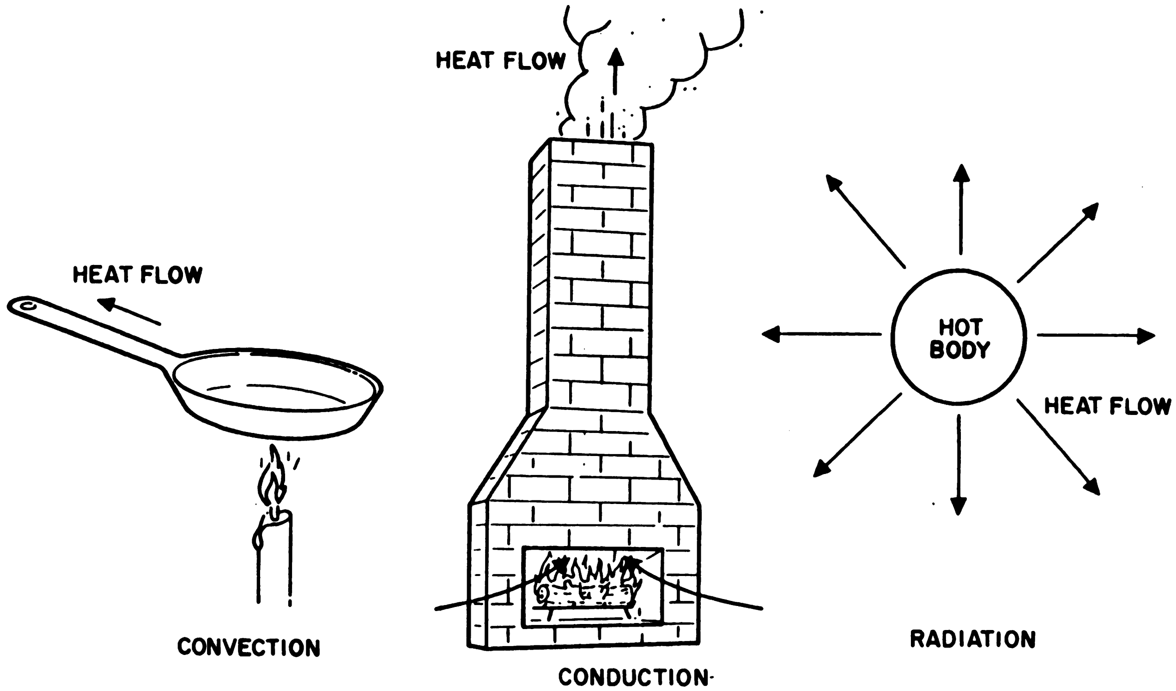

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Figure 3-35.—Heat flow, conduction, convection, and radiation.

Heat will flow between two systems when one system is at a higher temperature than the other. Heat will flow in the opposite direction (away from the higher temperature) only if work is done to the system (as in a refrigeration system).

There are three types of heat flow: convection, conduction, and radiation (fig. 3-35). *Convection* is the transfer of heat through macroscopic movement of material. (Macroscopic meaning large or visible as opposed to microscopic [small or invisible].) *Conduction* is the transfer of heat through materials when there is no macroscopic motion, as in the heat flow in metals. The rate of heat flow depends upon the following physical situations: (1) the higher the temperature gradient, the greater the rate of heat flow (the temperature gradient is equal to the difference in temperatures divided by the distance over which the heat must flow); (2) the larger the area across which the heat is flowing, the higher the rate of heat flow; and (3) the shorter the distance the heat must flow, the higher the rate of heat flow. *Radiation* is the transfer of energy by electromagnetic radiation. All bodies which have a temperature greater than 0 K give off electromagnetic radiation. The higher the temperature, the greater the amount of radiation emitted.

2. *The* **first law of thermodynamics** *states that the change in the internal energy of a system is equal to the heat introduced into the system minus the energy expended by the system when it does work on the environment.*

3. *The* **second law of thermodynamics** *states that a cyclic process must transfer heat from a hot reservoir if it is to convert heat into energy.* Also, work must be done to transfer heat from a cold reservoir to a hot reservoir.

4. *The* **third law of thermodynamics** *states that it is not possible by any procedure, no matter how idealized, to reduce the temperature of any system to absolute zero in a finite number of steps.*

Absolute zero is a limit that can only be approached, never achieved. The lowest temperature that has ever been attained is .00002 K. The closer that a system gets to 0 K, the harder it is to get heat from the system.

PRINCIPLES OF REFRIGERATION

Refer to figure 3-36 during the following discussion. The working fluid used in the system is CCl_2F_2 (Freon). The compressor (A) delivers gas at high temperature and pressure to the coils (B). Heat is removed from the gas in B by water or air cooling, resulting in condensation of the gas into a liquid. The liquid is forced through a small orifice (C) and expands as it leaves the orifice. It leaves the valve as a mixture of liquid and vapor at a lower temperature. The mixture of liquid and vapor now enters the coil (D) and heat from the surrounding area is supplied to the working fluid, converting the remaining liquid to a gas. The gas enters the compressor, and the cycle is repeated.

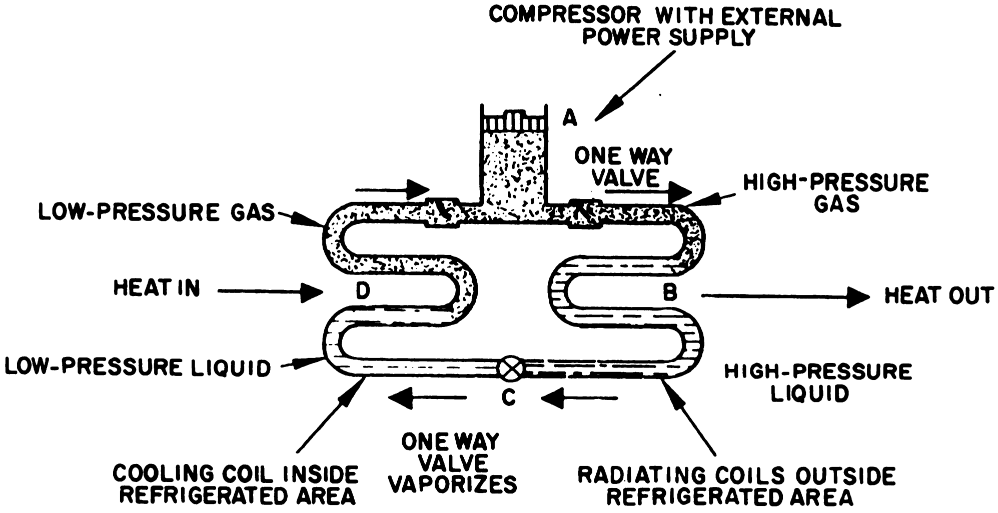

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Figure 3-36.—Common refrigeration cycle.

DETECTING-RANGING SET (DRS) AN/AAS-33A

The Detecting-Ranging Set (DRS) AN/AAS-33A is part of the A-6E integrated weapons system. The DRS provides three electro-optical sensors and associated controls and indicators to enhance the all-weather capability of the weapons system to detect, recognize, and identify targets accurately.

NOTE: While reading this section, you should refer to table 3-2 for a listing of the components and associated assemblies of the AN/AAS-33A.

Table 3-2.—AN/AAS-33A Components

Ref Des	Nomenclature	Placard or Common Name
	Components	
89A1	Receiver Group OR-203/AAS-33A or OR-203A/AAS-33A	Receiver group (RG)
	Major SRAs:	
	1. Forward Looking Infrared Receiver	FLIR receiver
	2. Laser rangefinder/Designator or Laser Receiver-Transmitter (LRT)	Laser rangefinder designator (LRD) or laser receiver-transmitter (LRT)
	3. Forward Air Controller Receiver	FAC receiver
	4. Turret Stabilized Platform	Turret stabilized platform (TSP)
89A2	Reciprocating Compressor HD-1032/AAS-33A	Compressor
89A3	Power Supply PP-7417/AAS-33A	Low voltage power supply (LVPS)
89A4	Generator Processor 0-1761/AAS-33A	Laser transceiver electronics (LTE)
89A5	Signal Processor CV-3460/AAS-33A	Laser receiver electronics (LRE)
89A6	Electronic Control Amplifier AM-6959A/AAS-33A	Electronic control amplifier (ECA)
89A7	Infrared Indicator IP-1301/AAS-33A	Forward looking infrared indicator (FLIR) indicator)
89A8	Detecting-ranging Set Control C-10301/AAS-33A	DRS control panel
89A9	Temperature Control C-10358/AAS-33A	-
	Cable Assembly W1 of AN/AAS-33A	Pulse forming network cable (PFN cable)
89A10	3-Way, 2-Position, DRS Solenoid Selector Valve	Solenoid selector valve

Table 3-2.—AN/AAS-33A Components—Continued

Ref Des	Nomenclature	Placard or Common Name
Associated Assemblies		
02A2	Nosewheel Well Circuit Breaker Box (Forward)	Nosewheel well circuit breaker panel (FWD)
02A3	Bombardier/Navigator Circuit Breaker Panel	-
02A11	Nosewheel Well Circuit Breaker Panel (Aft)	CB panel (NWW) (Aft)
03A2	Top Deck Relay Box	-
14A10	Temperture Control Box	-
23A1	Caution Dim and Test Light Assembly	Caution lights panel
50A1	Ballistics Computer CP-985/ASQ-133 or CP-1391/ASQ-155A	Ballistics computer
50A3	Computer Control C-9535/ASQ-155	Pedestal control unit (PCU)
50A10	Analog-to-Digital/Digital-to-Analog Converter CV-3163/ASQ-155	A/D converter
61A1	Mission Recorder Electronics Unit MX-9276/USH-17(V)	Electronics unit
61A3	Mission Recorder Control Panel C-9071/USH-17(V)	MISSION RECORDER control panel
75A4	Power Supply PP-6574/APQ-148	Low-voltage power supply (LVPS)
75A12	Analog Display Indicator IP-722D/AVA-1 or IP-722F/AVA-1	ADI
75A15	Fault Locating Indicator ID-1933/APQ-156	BIT panel
75A16	Pilot's Control Box	PCB
S67	Nose Gear Down and Locked Switch	-
S6030	Right Main Gear Weight-on-Wheels Switch	-

The physical location of the AN/AAS-33A within the aircraft can be seen by referring to figures 3-37 through 3-42.

The three sensors are housed in a 20-inch, fully gimballed turret and are collectively known as the receiver group (RG). This group is installed in the aircraft underneath the radome, forward of the nosewheel. The three sensors are the laser rangefinder/designator (LRD), forward air controller (FAC) receiver, and forward looking infrared (FLIR) receiver. The LRD is also known as the laser receiver-transmitter. The LRD functions as a range finder and target designator. It provides range-to-target data to the ballistic computer set and designated targets for laser-guided bombs (LGBs). The FAC receiver is used as an aid for the bombardier/navigator (B/N) in locating a target designated by an external laser source from a ground observer or

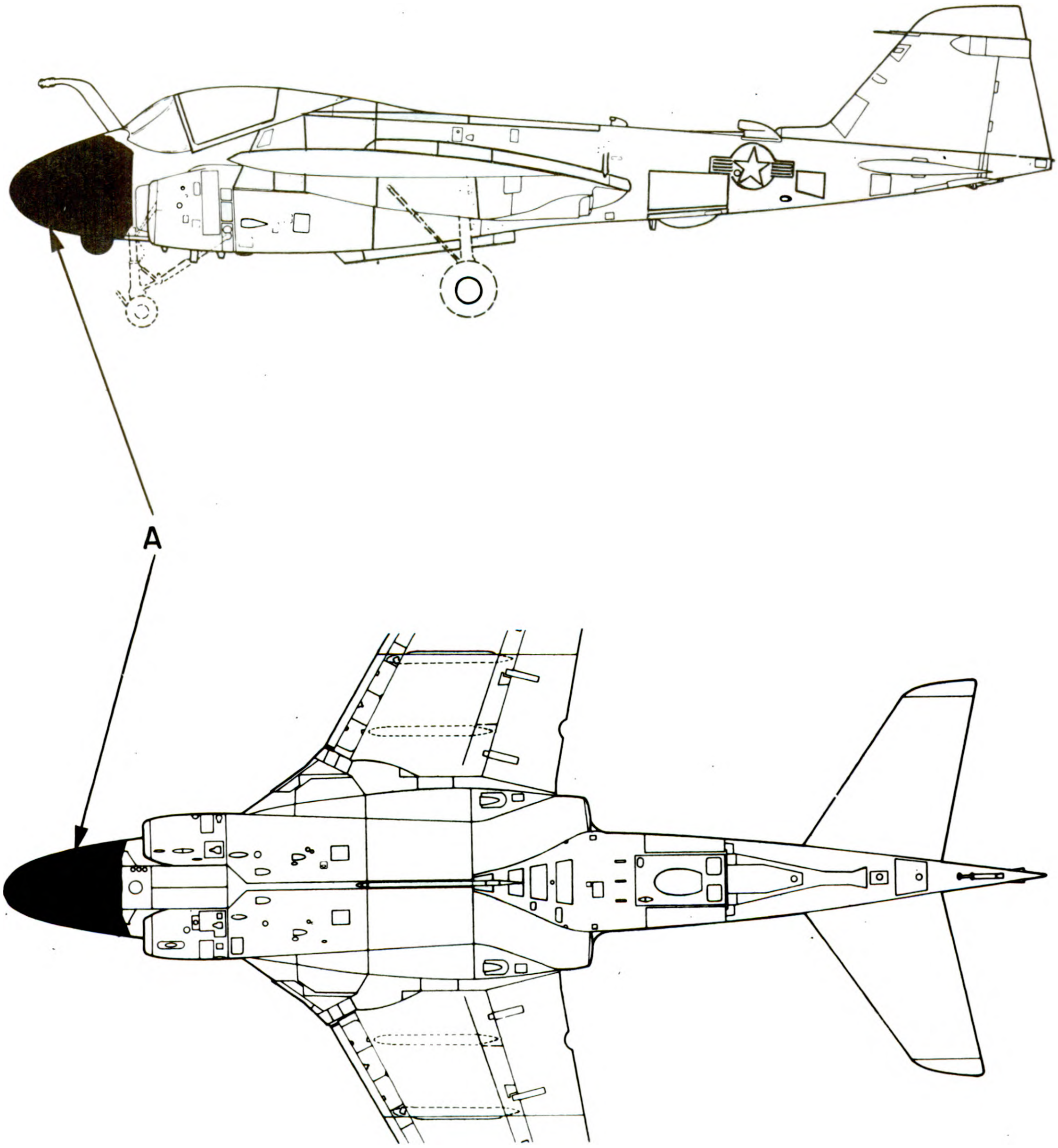

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Figure 3-37.—Outside view A-6E.

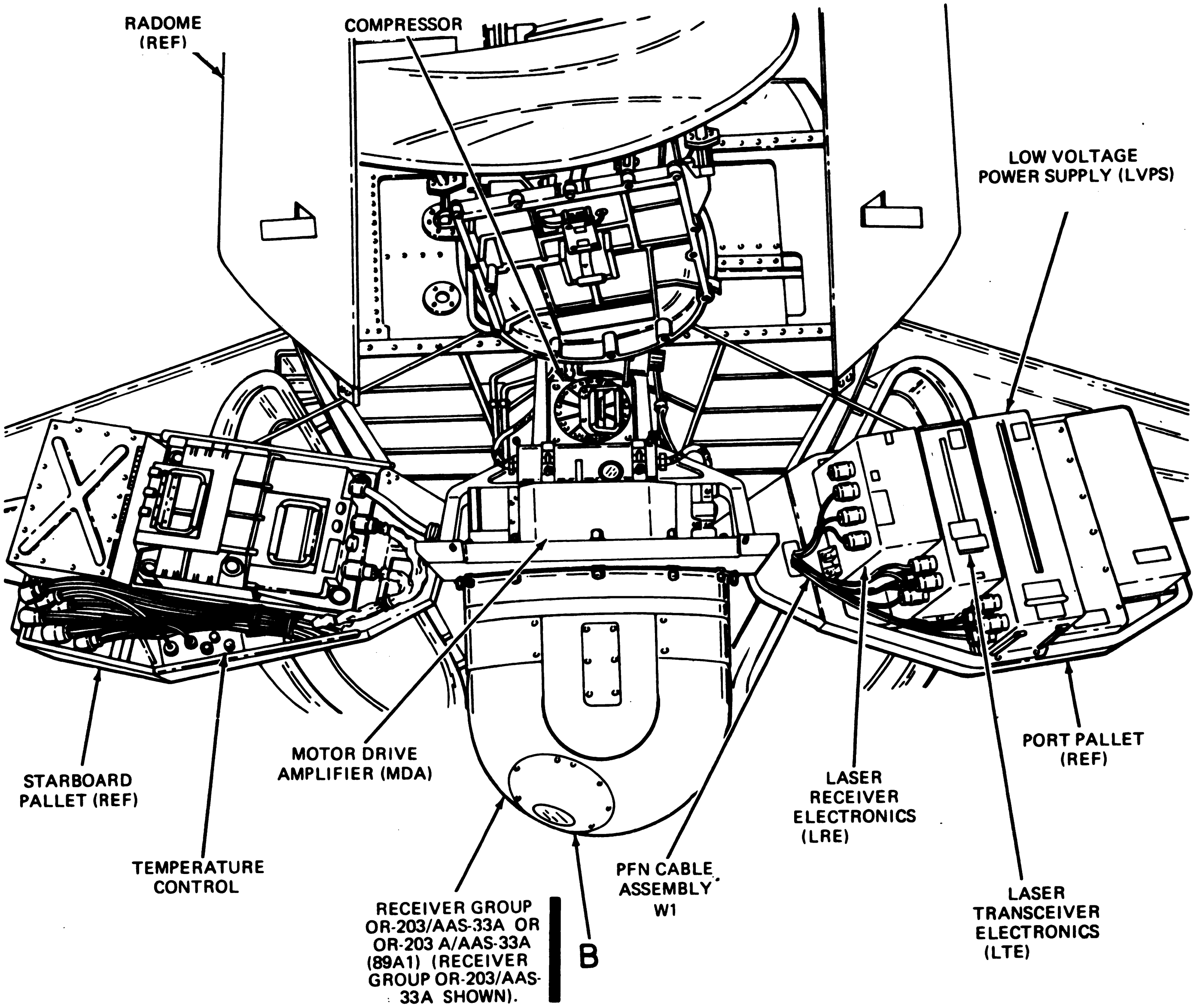
RADOME (REF)
COMPRESSOR
LOW VOLTAGE POWER SUPPLY (LVPS)
STARBOARD PALLET (REF)
MOTOR DRIVE AMPLIFIER (MDA)
PORT PALLET (REF)
LASER RECEIVER ELECTRONICS (LRE)
TEMPERATURE CONTROL
PFN CABLE ASSEMBLY W1
RECEIVER GROUP OR-203/AAS-33A OR OR-203 A/AAS-33A (89A1) (RECEIVER GROUP OR-203/AAS-33A SHOWN).
B
LASER TRANSCEIVER ELECTRONICS (LTE)

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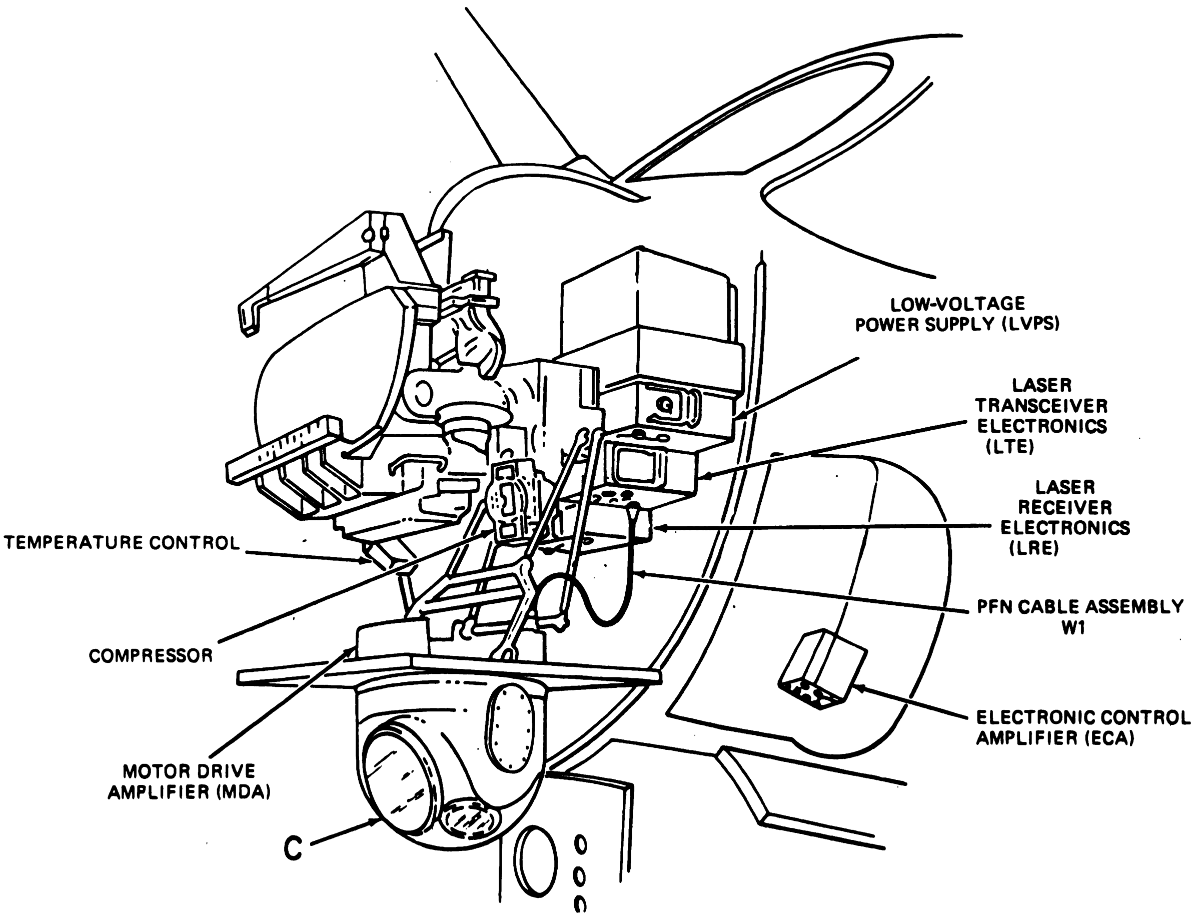
Figure 3-38.—Aft view with pallets extended and radome raised.


LOW-VOLTAGE POWER SUPPLY (LVPS)
LASER TRANSCEIVER ELECTRONICS (LTE)
LASER RECEIVER ELECTRONICS (LRE)
TEMPERATURE CONTROL
PFN CABLE ASSEMBLY W1
COMPRESSOR
ELECTRONIC CONTROL AMPLIFIER (ECA)
MOTOR DRIVE AMPLIFIER (MDA)
C

223.304

Figure 3-39.—View looking inboard and aft with pallets stowed.

another aircraft. A laser source can serve as the offset aimpoint in the solution of a computer-controlled bombing attack. The FLIR receiver is a passive sensor that is used to detect targets of interest by their emitted infrared radiation. The infrared radiation signals are processed and a real-time, television-like image is displayed on the FLIR indicator.

SYSTEM SHOP REPLACEABLE ASSEMBLIES (SRAs) AND THEIR FUNCTION

The turret stabilized platform (TSP) consists of a two-axis turret and a vernier two-axis gimbal that provides azimuth coverage of −195° and elevation coverage of +20° to +180°. A turret stow position of 0° azimuth and −210° elevation protects the three optical windows of the lower ball when the receiver group is not in the on-target mode of operation. A hydraulic motor connected to the aircraft hydraulic system provides power for turret outer azimuth drive. The elevation axis and inner gimbal drives are powered electrically.

FLIR RECEIVER

The FLIR receiver provides infrared target detection and recognition capability. It has a continuous optical zoom ratio capability of 5 to 1 (5x). A counterbalance weight moves in an opposing motion to the zoom to maintain a balance when the FLIR is installed in the TSP.

LASER RANGEFINDER DESIGNATOR (LRD)

The LRD provides target ranging and designating capability. It contains separate

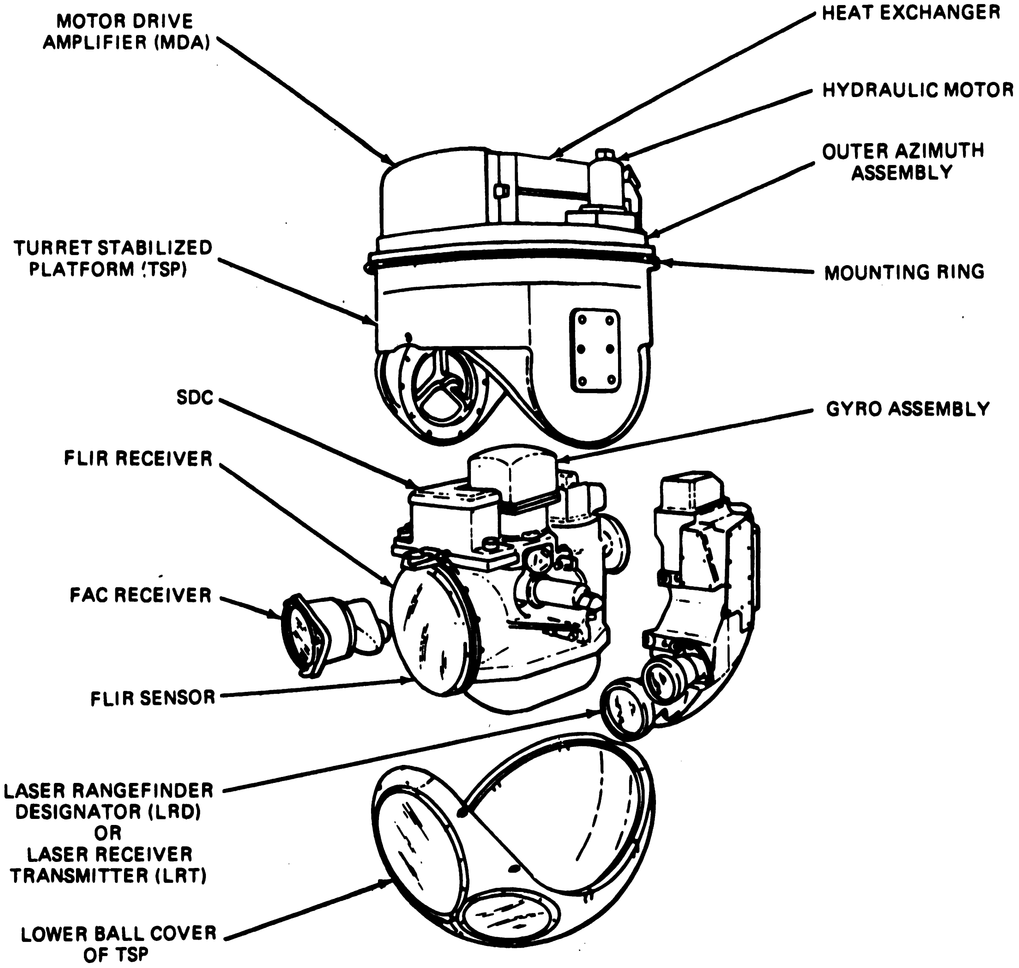


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Figure 3-40.—Receiver group.

telescopes for its transmitter and receiver, which view through a common window on the TSP. Computer control of range-finding and target designation modes is provided.

FORWARD AIR CONTROLLER (FAC) RECEIVER

The FAC receiver provides position information of acquired targets that are illuminated by remotely operated ground or airborne laser designators. It receives the laser energy through a separate window on the TSP. A four-quadrant detector generates the position signals, which are processed to locate the position of a target symbol displayed on the FLIR indicator.

RECIPROCATING COMPRESSOR HD-1032/AAS-33A

The HD-1032/AAS-33A compressor is a piston device that is driven by a 115-V ac, 400-Hz, 3-phase induction motor that is an integral part of the compressor assembly. The compressor provides helium pressure pulses for the required cooling for the detectors.

ELECTRONIC CONTROL AMPLIFIER (ECA) AM-6959/AAS-33A

The ECA contains the electronics circuits that provide the capability to accurately position or show the receiver group up to 1 radian/sec in response to input signals from the ballistic computer.

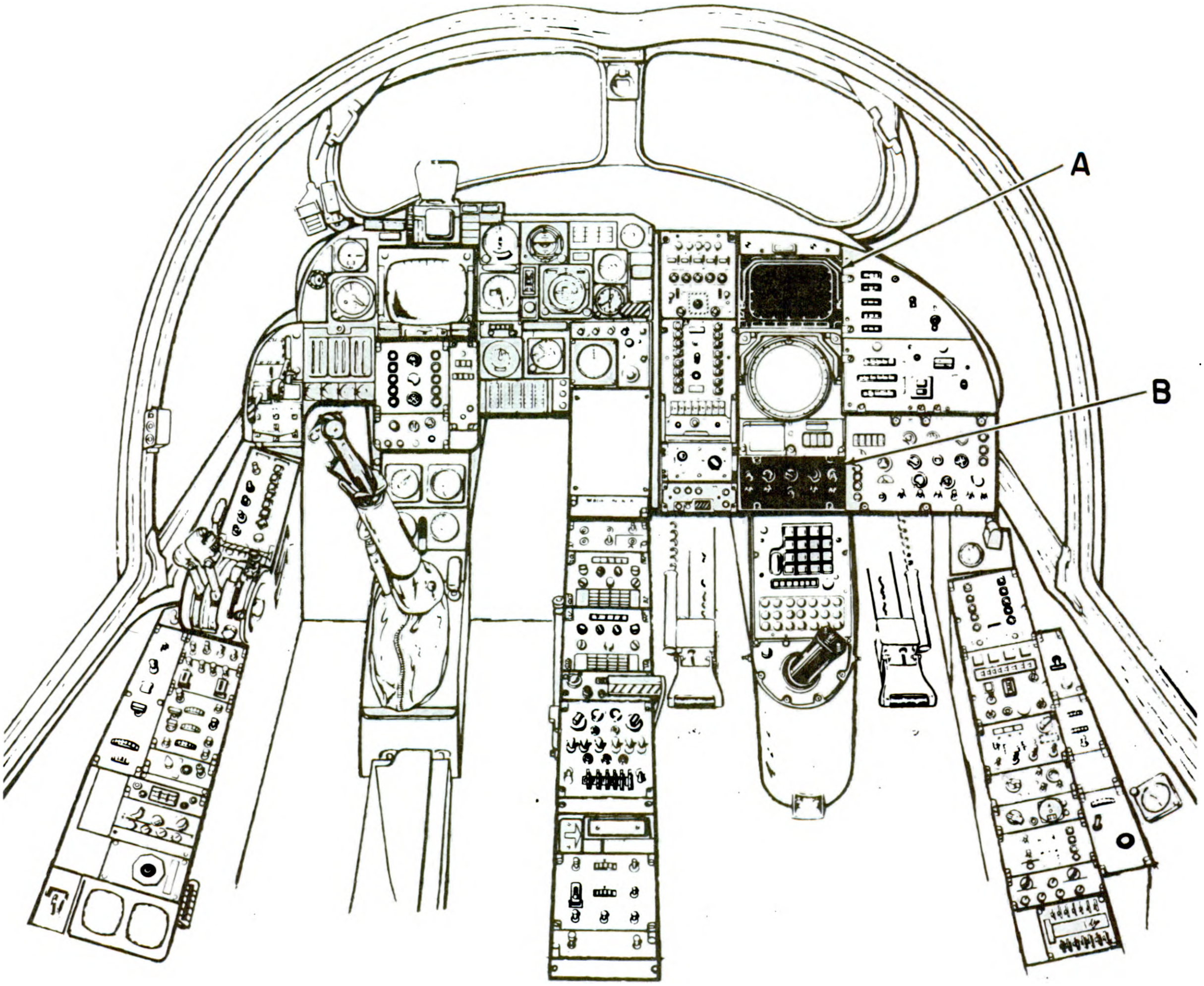

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Figure 3-41.—Cockpit.

GENERATOR PROCESSOR 1761/AAS-33A

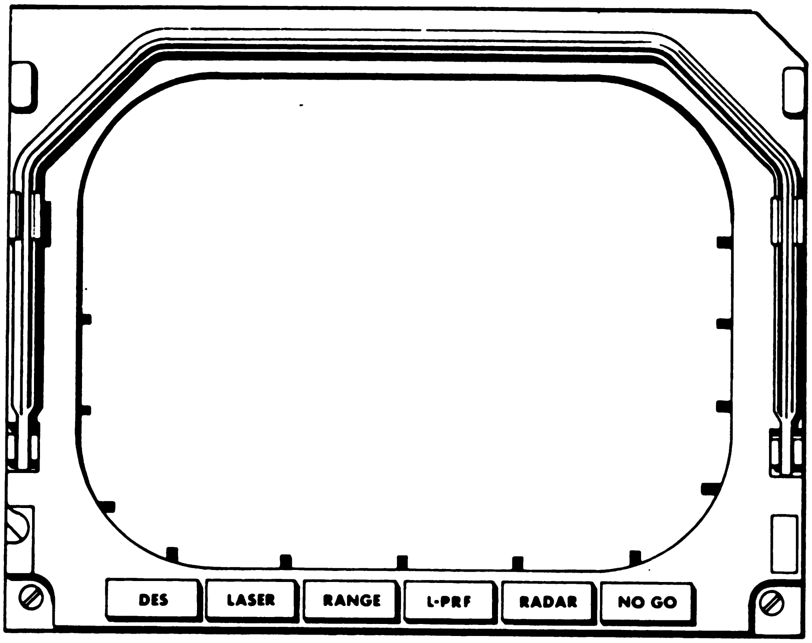
The generator processor is also known as the *laser transceiver electronics (LTE)*. It provides precise timing signals and a high-voltage firing pulse to the LRD. All mode commands and power for the laser subsystem interface with the rest of the DRS through LTE.

SIGNAL PROCESSOR CU-3460/AAS-33A

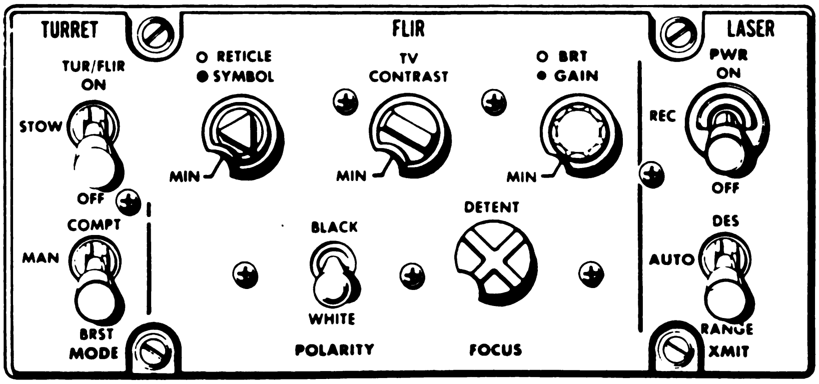
The signal processor is also known as the *laser receiver electronics (LRE)*. It processes four video signals from the FAC receiver, which are proportional to the position of a designated target in the FAC receiver field of view.

INFRARED INDICATOR IP-130/AAS-33A

The infrared indicator presents a high-resolution video display of the infrared scene in real time on an 8-inch diagonal CRT. In-flight video tape recordings can be made and played back on the infrared indicator. Six status lights on the front panel provide the B/N with the operating status of the DRS subsystem.



INFRARED INDICATOR
(FLIR INDICATOR)
A



DRS CONTROL PANEL
B

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Figure 3-42.—FLIR indicator and control panel.

DETECTING-RANGING SET (DRS) CONTROL C-10301/AAS-33A

The DRS control panel provides on/off power and mode command control logic for FLIR, stabilization, laser, and FAC subsystem operation. It also has controls for the FLIR indicator and FLIR subsystem. The DRS control panel also houses the BIT interface circuits between the aircraft BIT panel and the DRS WRAs.

POWER SUPPLY PP-7417/AAS-33A

The low-voltage power supply (LVPS) generates the low voltage necessary to operate the entire DRS system.

CABLE ASSEMBLY WI (PFN CABLE)

The PFN cable conducts the pulse forming network voltage from the LTE to the receiver group.

REFERENCES

Detecting-ranging AN/AAS-33A Principles of Operation, NAVAIR 01-85ADF-2-22, Naval Air Systems Command, Washington, D.C., 15 May 1983 through change 1 Aug 83

The Laser Safety Manual, E0410-BA-GYD-010/7034

CHAPTER 4

TYPICAL AIRBORNE MISSILE CONTROL SYSTEM

The Aviation Fire Control Technician is primarily concerned with missile guidance and control equipment installed in the aircraft. The missile itself contains guidance and control equipment, and it is essential that you understand the fundamentals of missile guidance and control relative to the missile itself. When you finish this chapter you will be able to—

- Identify the problems and basic fundamentals of missile control
- Recognize the basic operation of a missile control system
- Identify the intercept system to include the theory of operation and its phases of operation
- Identify the principle of operation and basic unit functions of a CW radar set

FUNDAMENTALS OF MISSILE GUIDANCE AND CONTROL

To understand the problems involved with effectively directing a missile to the target, you should become familiar with the fundamentals of missile guidance and control. Guided missiles differ from gun and rocket projectiles. Gun and rocket projectiles are committed to a given course at the instant of firing, while the course of a missile is altered during flight. The missile fire control problem is continuously solved through the performance of the following functions: (1) tracking; (2) computing, (3) directing, and (4) steering.

The necessary components for the performance of all the functions may be located entirely within the missile itself, or some may be located in the launching aircraft. The Aviation Fire Control Technician is primarily concerned with those components located in the aircraft.

A precise comparison between the gun and rocket fire control problem and the missile fire control problem is difficult to make. In naval aircraft, the gun and rocket fire control problem is continuously solved from the start of the run until the projectile is fired. The solution of the missile fire control problem continues until the missile strikes the target.

MISSILE FIRE CONTROL PROBLEM

There are three phases to the missile fire control problem: (1) prelaunch aiming, (2) guidance, and (3) control. These phases determine the proper flight path for the missile, and they control the missile so that it follows this path.

Prelaunch Aiming Phase

The prelaunch aiming phase is similar to the aiming problem for unguided weapons (guns and rockets), but it has a wider tolerance for aiming errors. It might also be considered as an essential part of the guidance phase.

Guidance Phase

The guidance phase of the missile fire control problem is that portion of the problem that determines the missile's course to the point of interception with the target. The guidance system performs three functions: tracking, computing, and directing.

NOTE: Guidance in semiactive homing usually involves the use of the radar and computing equipment necessary to determine how a missile's course must be changed to intercept the target.

Tracking is the process of continuously determining the relative positions of the target and the missile. Tracking may be done by visual observation, the use of radar, or any other process that uses some distinguishing feature of the target. The tracker may be located in the missile or in the launching aircraft.

Computing is the process of determining course corrections (both in magnitude and direction) that the missile makes to score a hit. The computing system may be elaborate or simple, but all systems use tracking data received from the tracking system. The computing equipment may be installed in either the missile or the launching aircraft.

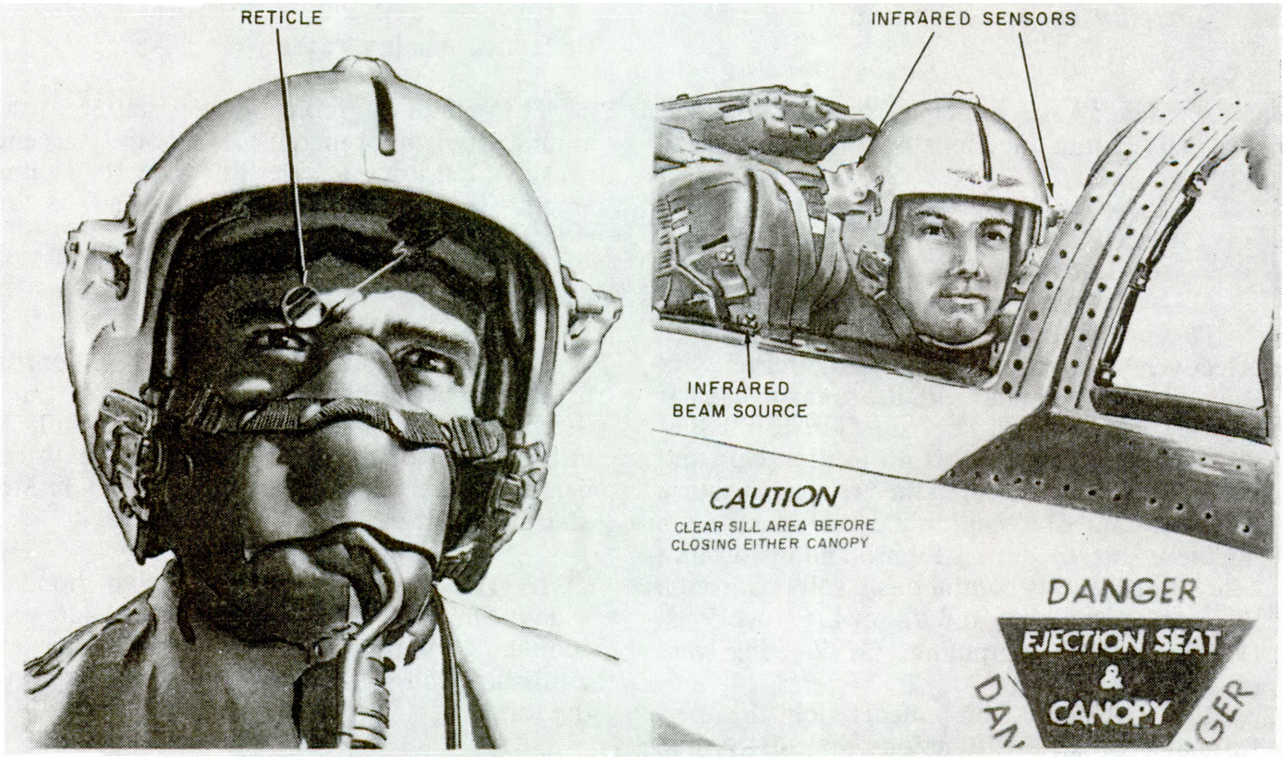
Directing is the process of directing or telling the missile what course corrections to make. The output of the computing system furnishes correction data that is transmitted to the missile's control system to accomplish steering. A computing system that is located in the launching aircraft transmits course correction data to the missile. Radio waves are normally used to complete the data transmission loop.

Control Phase

The control phase is concerned with the performance of the steering function. The steering function deals with the aerodynamic portion of the missile fire control problem. When properly performed, steering provides a smooth and stable flight of the missile. The steering function is performed by a control system that consists of equipment required to convert steering or guidance signals to movement of the missile's control surfaces. The control system is contained entirely within the missile. As such, it is of little concern to the AQ, except to provide a better understanding of the overall system.

METHODS OF GUIDANCE

As compared to surface-to-surface operations, the target of air-to-air missile operations is located near the launching platform. Usually, the target is also relatively small and highly maneuverable. The required guidance method must be capable of making continuous corrections to the flightpath, and it must be able to respond rapidly to changes in the position of the target. The guidance system must be suitable for use with maneuverable launchers, since air-launched missiles are carried either on pylons attached to the wing or fuselage



223.74

Figure 4-1.—Visual target acquisition system.

or on some enclosed or retractable mechanism. The guidance methods most suitable for these conditions are the visual target acquisition system (VTAS), the beam rider, and homing.

VTAS Method

Figure 4-1 shows the visual target acquisition system. VTAS allows a pilot or crew member to aim an AIM-9 Sidewinder missile by turning his head and looking at a target. A small retractable glass reticle is mounted on the helmet and snaps down in front of one eye. Two infrared sensors are also mounted on the crew member's or pilot's helmet, and two beams of infrared light are emitted from two sources mounted in the cockpit aft of the pilot's shoulders.

The two infrared sources produce two fanlike beams that rotate at a constant velocity. When the difference in their time of arrival at the two infrared sensors is compared with the arrival of a fixed reference sensor, the azimuth and elevation position of the helmet is found and converted into azimuth and elevation angles by a digital computer, which is also part of the system. Therefore, the pilot or crew member need only look at the target and the elevation/azimuth look angles are transmitted to the Sidewinder missile's guidance head.

Beam-Rider Method

In the operation of the beam-rider method, the target is tracked by a radar beam (usually that of a radar set carried by the launching aircraft). The missile responds to the beam by means of a receiver. The output of the receiver consists of error signals which, when applied to the control system, cause the missile to remain in the center of the radar beam until it collides with the target. Figure 4-2 shows the beam rider guidance method.

Missiles controlled by the beam-rider method are directly controlled by the launching aircraft radar. Once the target has been acquired by the aircraft radar, automatic tracking devices keep the radar beam continuously on the target. An automatic homing device may also be used to control the missile during the final stage of its flight.

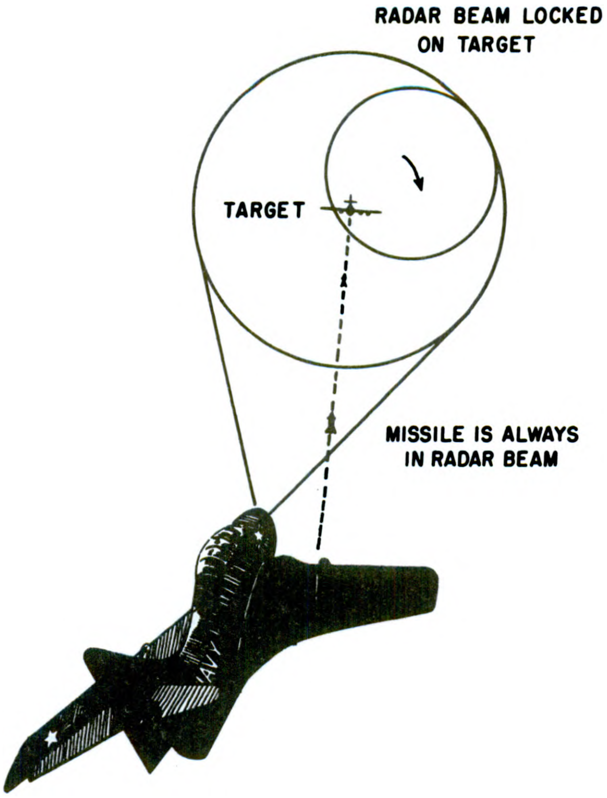


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Figure 4-2.—Beam rider guidance method.

Homing Method

With the homing method of guidance, the path of a missile can be changed after launching by a device in the missile that reacts to some distinguishing feature of the target—such as heat, light, or reflection of radar waves. A homing device, usually placed in the nose of the missile, picks out the target and then directs the missile to the target.

The best homing systems make use of heat radiation and reflection of RF energy. These systems are accurate, and the missile may be expected to hit its target if released within its range of operation.

There are three types of homing guidance systems: active, passive, and semiactive. In the active homing guidance system, both the transmitter (which illuminates the target) and the receiver (which receives the echoes) are carried within the missile. In the passive system, the missile uses radiations from the target. In the semiactive system, the receiver in the missile uses radiations from the target, which has been illuminated by a transmitter located in the launching aircraft.

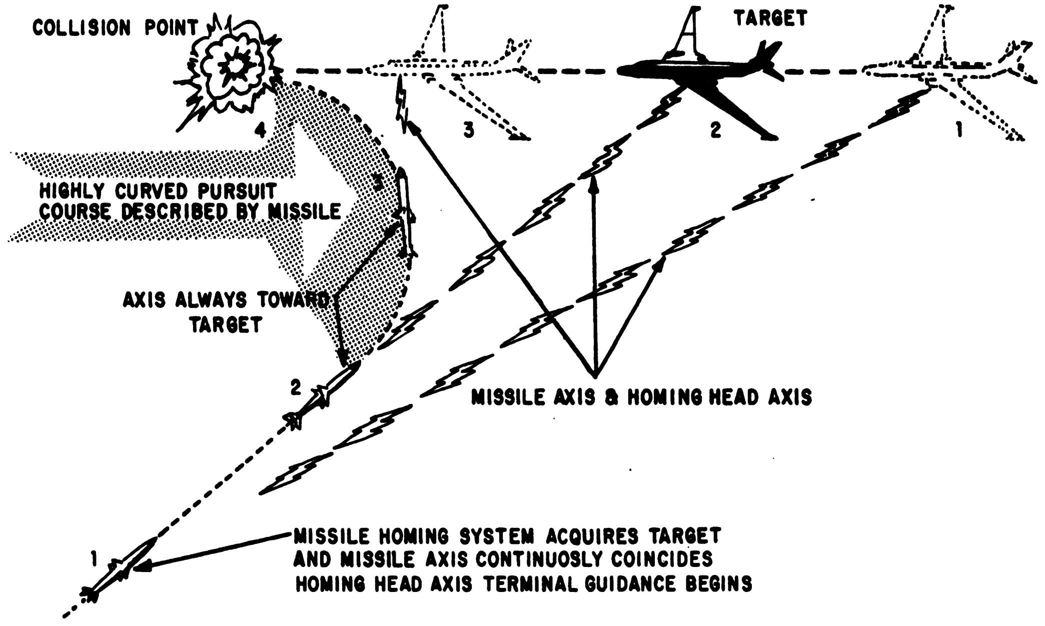
The homing device may control the path of the missile to a moving target in several ways. The more widely used systems are the pursuit-homing and lead-homing types. In these types of systems, the course flown by the missile approximates that of a lead collision course.

In pursuit homing, the guidance system causes the missile to point directly toward the target at all times. The homing device points directly ahead and keeps the heading of the missile the same as the direction of the target echoes. A missile flying a pursuit course experiences increasingly large *g* forces due to turning in the last portion of the course, as shown in figure 4-3. This part of the flight path is most critical. When the target is small or is not flying a collision course, accuracy is reduced. For this reason, pursuit homing does not have many applications against high speed targets.

In lead homing, a lead collision course is established when the path of the missile maintains a constant angle with the path of the target. In lead homing, the guidance system establishes a lead angle with the target and keeps this angle essentially constant so the missile travels directly toward a collision point, as shown in figure 4-4. This causes the missile to complete the final and critical part of the flight path on a straight line.

To effect a lead collision course, it is necessary for the guidance system to measure the rate at which the angle changes. This may be accomplished by having the homing device point toward the target. Any change in the direction of the target from the missile causes the homing device to turn. The rate at which it turns can be measured by a rate gyroscope. These additional functions require that the homing system for a lead course be more complex than a system for a pursuit course.

Range is one of the main limitations of homing systems. Also, homing devices must have high directional sensitivity so they will not be confused by multiple targets. Because of these problems, it is necessary to place the missile in the vicinity of the target and pointing toward the target. This may require the initial part of the course to be controlled by another


COLLISION POINT
TARGET
4
3
2
1
3
HIGHLY CURVED PURSUIT
COURSE DESCRIBED BY MISSILE
AXIS ALWAYS TOWARD
TARGET
2
MISSILE AXIS & HOMING HEAD AXIS
1
MISSILE HOMING SYSTEM ACQUIRES TARGET
AND MISSILE AXIS CONTINUOSLY COINCIDES
HOMING HEAD AXIS TERMINAL GUIDANCE BEGINS

223.76

Figure 4-3.—Pursuit homing.

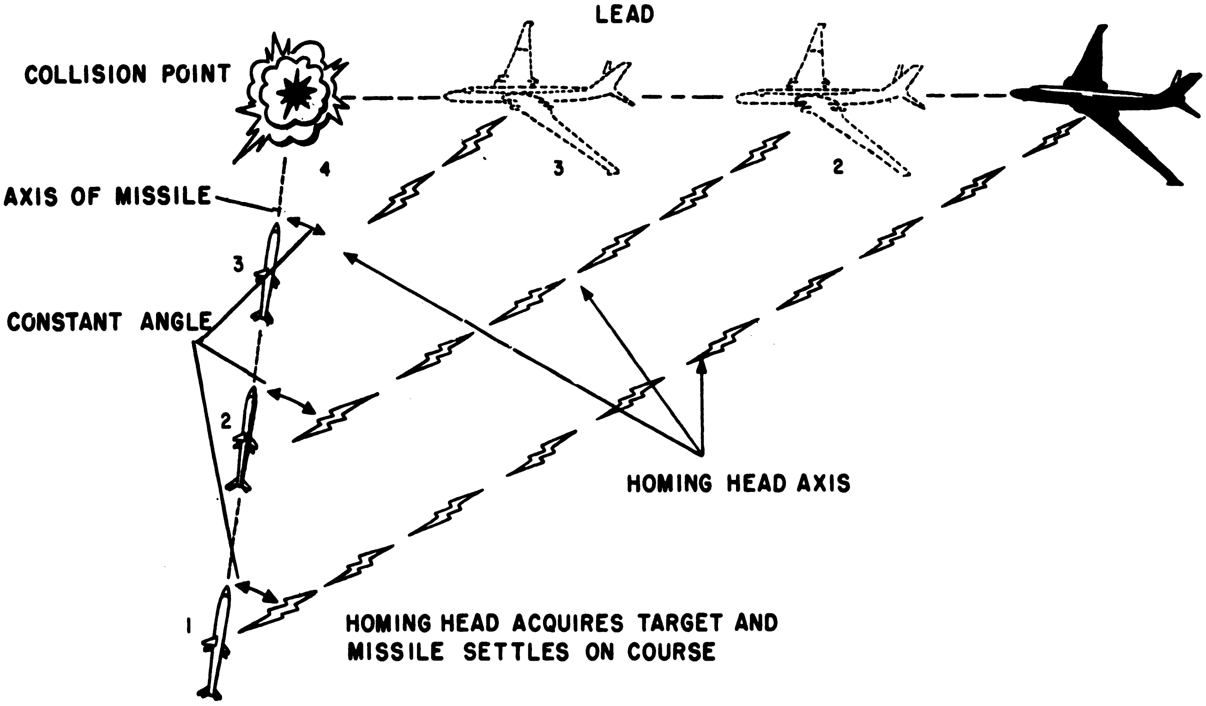


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Figure 4-4.—Lead Homing.

type of guidance system, such as the beam-rider system.

A TYPICAL MISSILE CONTROL SYSTEM

The primary purpose of the airborne missile control system (AMCS) is to assist the pilot in carrying out attacks against enemy aircraft with a high probability of success under all environmental conditions. The intercept problem posed by this type of mission requires that the system enables the pilot to navigate to the target area, find and identify the target, acquire the target, and track it throughout the attack. The system must present steering information to the pilot by means of a radar indicator. A typical missile control system capable of solving the missile fire control problem consists primarily of two items:

1. An intercept system consisting of an intercept pulsed radar and a computer group
2. A continuous wave (CW) radar group

Additional components may be required to make up the complete system; for example, a flight data unit, a vertical gyro unit, and a launching set.

Before the guided missile can be launched, the missile control system must supply the missile with certain data. The intercept radar set determines range and develops a proportional voltage supplied to the computer group and the CW radar group.

The CW radar group generates CW-RF energy that is injected into the waveguide assembly and transmitted by the intercept radar antenna. The CW radar also develops a pseudo signal that is fed to the missile for the purpose of checking the operation of the missile's circuitry in the Doppler frequency region. When the target is within range, the pseudo signal is cut off. Now, the CW radar group develops a simulated Doppler signal proportional to the closing range rate. This simulated Doppler signal is fed to the missile to tune the missile circuitry to the anticipated Doppler frequency region. It should also be noted that the CW radar supplies in-range information to the missile launching set.

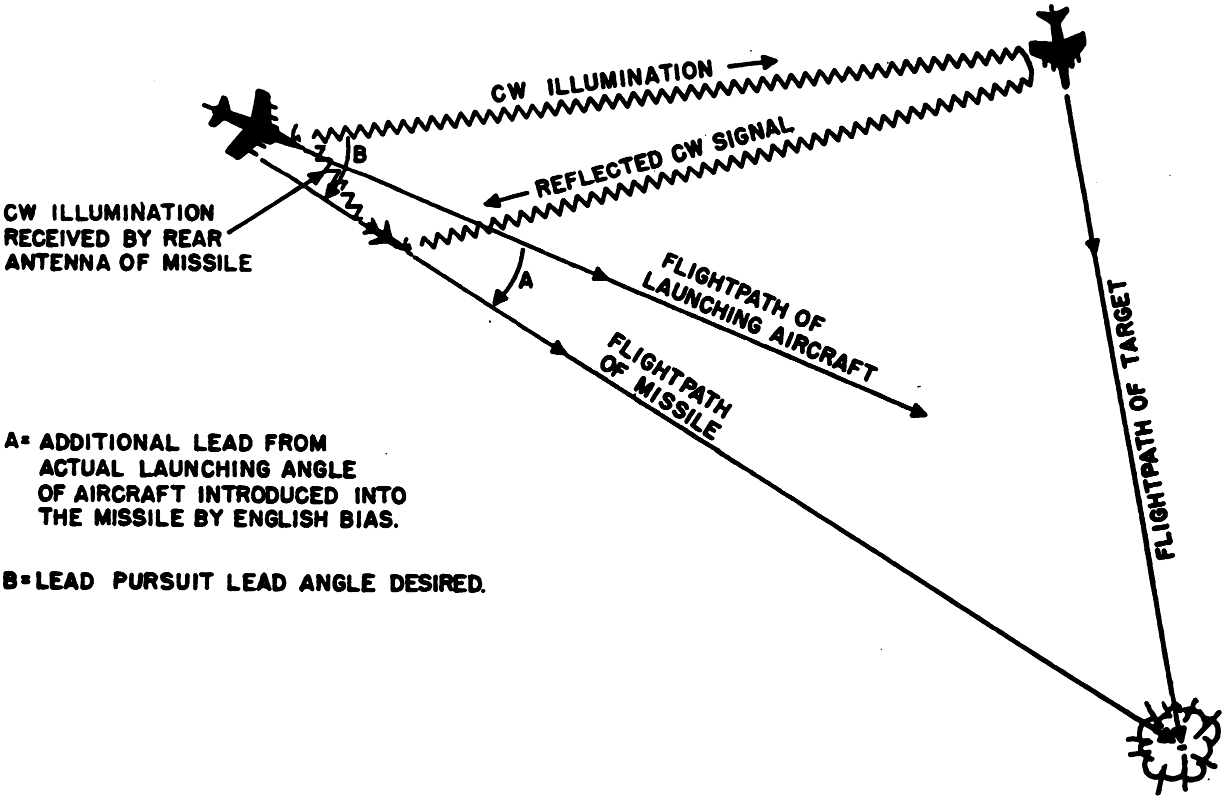
In order to understand the operation of the various functions of the AMCS system after launching, the use of the CW radar is discussed first. Figure 4-5 shows a typical missile attack problem. The CW signal is transmitted by the intercept system's antenna and, when reflected by the target, is received by the missile's nose antenna.

The rear missile antenna receives the CW signal directly from the intercept radar antenna. Then, both signals are compared in the missile's receiving system. Because the distance between the missile and the target is decreasing, the signal received from the target is changed in frequency with respect to the signal received directly from the intercept antenna. The difference between the two is the Doppler frequency, which is directly proportional to the closing speed.

The Doppler signal is applied to the speed gate where it is compared to a reference signal. The speed gate prevents the missile from homing on some other object near the target but moving at a different velocity. Steering signals are provided within the missile by deriving error signals from the conical scan antenna when homing on the reflected CW energy from the target. The missile uses the constant look-angle method of homing on a target. Coding and range modulation are used to prevent interference and to measure the range to the target.

The intercept radar is used to detect and track the aircraft targets. At the time of a launch, the intercept radar antenna position information is fed to the missile's nose antenna for the purpose of properly positioning it for target acquisition. Head-aim and English-bias information is provided to the missile that will insert any correction required in the event the launching aircraft is not on the exact lead pursuit course. After the intercept radar has locked on a target and the missile to be fired has been selected and armed, the pilot can fire the missile when the in-range signal comes on, provided his target is within the allowable steering error (ASE) circle.

Look at figure 4-5. The lead pursuit course that the launching aircraft attempts to fly is shown by angle B. Because of limitations in aircraft performance or heading errors on the part of the pilot, the aircraft may not be able to fly an exact lead pursuit course. In this event, a heading correction voltage (head-aim and English-bias)


CW ILLUMINATION →
← REFLECTED CW SIGNAL
B
A
CW ILLUMINATION RECEIVED BY REAR ANTENNA OF MISSILE
FLIGHTPATH OF LAUNCHING AIRCRAFT
FLIGHTPATH OF MISSILE
FLIGHTPATH OF TARGET
A= ADDITIONAL LEAD FROM ACTUAL LAUNCHING ANGLE OF AIRCRAFT INTRODUCED INTO THE MISSILE BY ENGLISH BIAS.
B= LEAD PURSUIT LEAD ANGLE DESIRED.

223.78

Figure 4-5.—Typical attack problem.

proportional to angle is supplied to the missile prior to launching in order to bring it on course immediately after launching. The heading correction is a dc voltage generated in the CW radar group and provided to the missile. It is used by the missile only after it has been launched.

INTERCEPT SYSTEM

The purpose of the intercept system is to provide the pilot and the radar intercept officer (RIO) with the information required to locate and select the desired enemy target for automatic tracking. When a target is being tracked, the radar provides other portions of the missile control system with the target information necessary to direct the interceptor to launch the missile and to compute the required missile guidance signals. The radar gives the pilot of the radar intercept aircraft the steering and missile-flying information required to fly the aircraft and to launch the missile to produce a kill. During search, the pilot and the radar intercept officer get range, bearing, and elevation on all targets detected from the radar.

During the track mode of operation, the pilot and radar intercept officer get range, bearing, and elevation of the target from the radar. The radar furnishes the same data, together with the line-of-sight rate, to the CW radar computer and displays aircraft steering error, attitude, and missile-firing information. The radar antenna transmits the CW illumination energy for guidance of the Sparrow III missile.

The intercept system has provisions for a Sidewinder extended acquisition mode (SEAM). The SEAM presentation consists of a circle and dot, and it is displayed when the AIM-9G missile head is locked on a target. The dot indicates the AIM-9G missile head position relative to boresight, and the circle represents a 20° angular displacement reference.

PHASES OF OPERATIONS

The operation of the system may be classified under four phases; each phase has one or more modes of operation. The phases of operation are standby, search, acquisition, and track. Each phase of operation is essential to the radar in accomplishing its purpose.

Standby

At times, radar silence must be maintained. When this is necessary, the equipment is placed in standby (the condition for passive search operation). The AMCS is able to detect a jamming source, acquire it, and angle track it. All antenna search patterns are available at this time. Full data link capabilities also are available during this mode. Angle track and data link are discussed later in this chapter.

Search

Look at figure 4-6. When the radar is in search condition, the radar intercept officer observes the indications on the radar to seek, identify, and select the target to engage. He does this whether the target is airborne or on the ground. Search operation is discussed in the following paragraphs.

In the normal search condition, the radar is in full operation. At this time the RIO can do the following:

- Arrange for the antenna to be driven in azimuth, either automatically or manually. Automatic scan can be limited to 30° in azimuth (narrow scan) or it can cover the entire display width (wide scan).

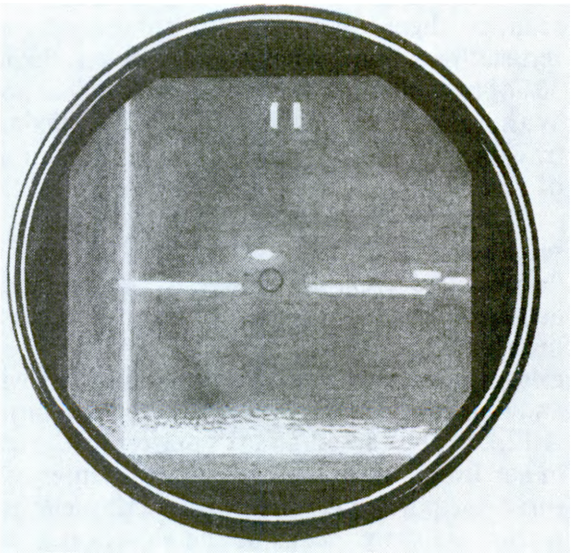


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Figure 4-6.—Radar presentation, search mode.

- Choose elevation antenna motion, either on one level or three levels (one-bar or three-bar scan). The elevation at which either scan takes place is manually controlled by the radar intercept officer.

- Select a display range of 10, 25, 50, 100 or 200 miles or expanded sweep sectors of 10 or 16 miles.

- Select one of two beam widths.

- Select one of three types of polarization.

- Select radar (air-to-air) or bomb mode (air-to-ground) operation.

The wide antenna scan is used when the aircraft is operating without ground control intercept (GCI) direction. While operating, the antenna scans back and forth in azimuth over an arc of 120° at the rate of 120° per second. The antenna hesitates at the end of each scan so that there will be no azimuth motion of the antenna if there is a change in elevation at this time, as in three-bar scan. The tilt of the antenna is adjusted by the RIO by means of the elevation control wheel on the radar control stick.

The narrow scan increases the detection capability of the system when the approximate position of the target relative to the aircraft is known. In this arrangement, the antenna moves at one-half the speed (degrees-per-second) of wide scan, so there are double the number of target returns per scan. The antenna moves through 30° of travel before returning to the original point. With only 30° scanned out of the 120° maximum travel available, it is possible to choose an area of search anywhere within the display area.

The three-bar scan is provided to increase the search area when the elevation of the target is not known. The RIO selects three-bar operation and at the end of each azimuth scan, the antenna jumps 3.75° in elevation. As a result, the overall elevation coverage (including antenna beam width and the effect of spinning the feedhorn (nutation)) is 12.2°. The three-bar scan pattern is the same in narrow or wide scan. The vertical center of the three-bar pattern can be positioned in elevation within ±50° by means of the elevation control wheel.

The one-bar scan is useful during search when the exact elevation is known, or on flights at low altitude during which a deeper scan could result in ground clutter pickup. In this pattern, the number of scans over a particular area-per-unit time is increased so that the chance of detecting a target at that elevation is also increased. Moreover, with the elimination of the elevation jump characteristic of the three-bar scan, the same information is painted over and over on the indicators, thereby improving the viewer's chance of seeing the target.

The polarization of the energy being transmitted can be controlled by the RIO for optimum system performance. In the radar mode, the RIO chooses either linear polarization or one of two available circular polarizations, depending upon the weather. In clear weather, linear polarization is normally used because it provides the greatest detection capability. In the presence of clouds, circular polarization may be advantageous because of the increased possibility of seeing through the cloud (fig. 4-7). The RIO can choose circular polarization in either direction by setting the POLAR switch on the radar set control at CIR 1 or CIR 2. During an air intercept, only LIN or CIR 1 can be used because they are compatible with the antenna on the Sparrow III missile.

During search, the RIO has the choice on one of two receivers. The selection usually depends upon the type of clutter encountered and the range under search. One of the receivers has the

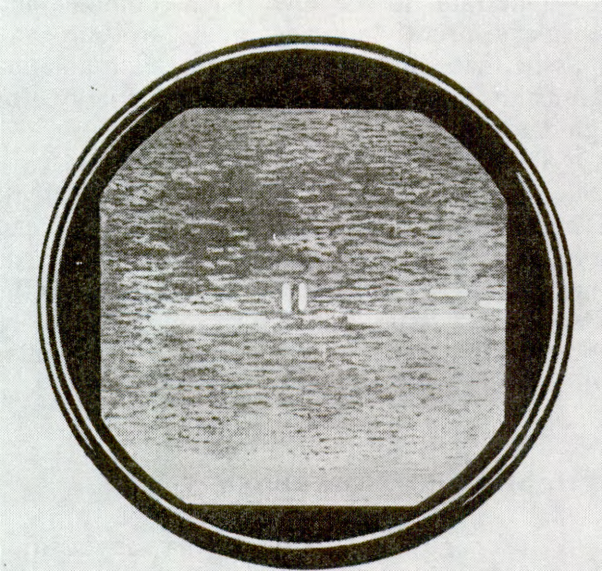

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Figure 4-7.—Radar presentation, showing weather.

capability of seeing through clutter, but with reduced detection capability (fig. 4-8).

A specialized method of search is available to the RIO for use at search display ranges of 100 to 200 miles. If the azimuth and elevation of the target are known to the RIO, maximum detection capability of the radar set can be achieved by stopping automatic search and manually positioning the antenna in the direction of the target. Then, spotlight operation can be used by pressing the lock-on switch on the radar control stick to the full-action position and manually positioning the antenna with the radar control stick. Nutation of the antenna feedhorn is stopped at this time to reduce antenna beam width to a minimum, so the maximum amount of RF energy is concentrated in the smallest area. Conversely, for additional azimuth and elevation coverage, the lock-on switch is returned to half-action position, restoring nutation.

Acquisition

Acquisition is the process of selecting and locking on a target. If it is successful, the radar is switched from search to the track condition. Various phases of acquisition are discussed in the following paragraphs.

In the normal acquisition process, the RIO moves the radar control stick so an acquisition symbol displayed on the indicator brackets the selected target. Then, the lock-on switch is pressed to the half-action position, causing the antenna to stop scanning and slew to the azimuth position of the acquisition symbol (fig. 4-9). At this time, a range strobe appears on the presentation as an intensified spot on the B-sweep, centered between the bars of the acquisition symbol. The radar control stick is then positioned to place the range strobe directly over the target dot. By moving the acquisition symbol and the range strobe to the target position, the RIO adjusts the radar circuits for acquisition. Now, the lock-on switch is pressed to the full-action position, and the radar automatically proceeds to acquire the target and start tracking.

If before acquisition, the radar had been searching in the three-bar scan pattern, the target return could have appeared on any of the three bars. Since the antenna is positioned on the center bar during acquisition, a target return on the center bar could, in some situations, be lost beyond the edge of the radar beam. To prevent such loss of targets, the antenna is made to nod 2° above and below the center bar elevation, in effect broadening the beam to include off-center returns.

Acquisition can be achieved only in the air intercept (AI) display ranges of the radar. If it is attempted in 100- or 200-mile display range, the

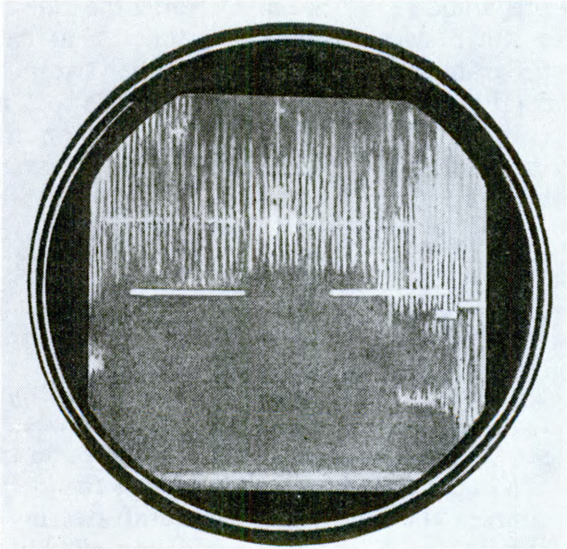

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Figure 4-8.—Radar presentation, showing clutter.

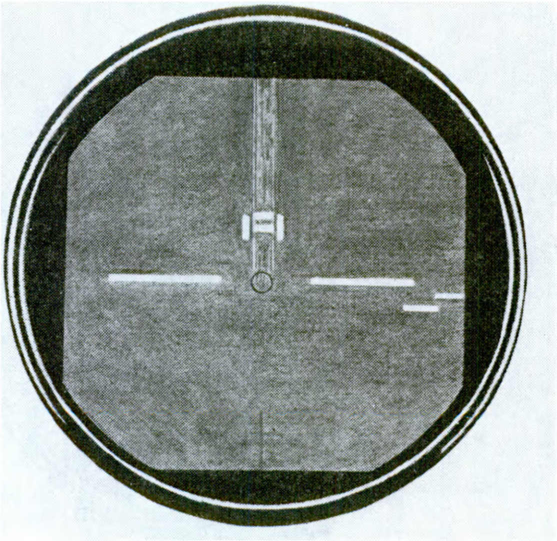

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Figure 4-9.—Radar presentation, acquisition mode.

system switches to the spotlight condition of search. The RIO can then maintain surveillance of the target until the range is suitable for acquisition. At that time, the RANGE switch is set for the desired AI range and normally acquires the target. It is also possible to have target presentation after lock-on if expanded sweep is used during search and acquisition. After lock-on, the system automatically returns to normal display range presentation. If the expanded sweep is delayed to present a range more distant than the setting of the RANGE switch but not exceeding the maximum AI range of 50 miles, and a target is acquired at that range, the target will not be within the display range after lock-on. Therefore, it will not be displayed; but, lack of a displayed target will not interfere with lock-on and normal tracking. Increasing the display range returns the target to the display.

If during search, a source of noise or CW jamming of sufficient strength to prevent normal acquisition is encountered, the jamming source itself can be used as the target, but only for angle tracking (fig. 4-10). Acquisition of the jamming source is less desirable than normal acquisition, because range information, normally available by radar, cannot be obtained from the direct transmission out of the jamming source.

In acquiring the jamming source the RIO brackets the azimuth position of the source with the acquisition symbol by means of the radar control stick, and then presses the lock-on switch to half action. If the target is still obscured by the jamming, the lock-on switch is pressed to full action. The system then automatically acquires the jamming source and starts angle track.

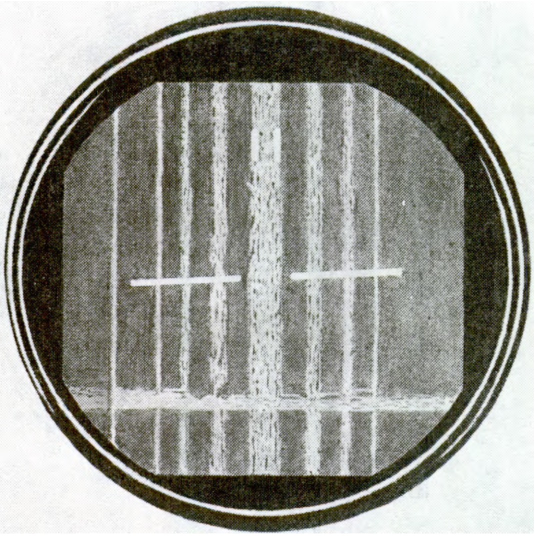

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Figure 4-10.—Radar presentation, acquisition on jam.

Under certain conditions, it may be desirable to track the target manually; for example, when a target is visible during jamming, but the jamming is preventing normal acquisition. To acquire a target for manual tracking, the RIO sets the TRACK switch on the radar set control at MAN, brackets the target with the acquisition symbol, and presses the lock-on switch on the radar control stick to half action. The antenna sweeps to the azimuth position of the acquisition symbol and the range strobe appears on the B-sweep. With the radar control stick, the RIO positions the range strobe just in-range from the target (closing target) and presses the lock-on switch to full action. The radar now switches to an aided manual track condition.

Another acquisition mode is labeled the pilot lock-on mode (PLM). PLM provides the capability of pilot-initiated acquisition and lock-on. In this mode, the pilot has priority for control of the radar. When the pilot's target acquisition enable switch (TAE) is pressed to half action, the antenna is commanded to a boresight position, and a 5-mile range B-sweep is selected for display. Flying a pursuit course, the pilot presses the TAE switch to full action. After a time delay, the full action command is passed to the synchronizer in preparation for lock-on. Also after the time delay, a range sweep strobe is initiated that can be programmed by the pilot to either sweep from 5 miles to 0.5 mile or from 0.5 mile to 5 miles (sweep IN or OUT). The target detector circuits in the synchronizer then compare the target return with the sweep strobe signal. When coincidence occurs in time, the radar locks on the target automatically, and angle track is initiated.

Track

Upon successful completion of acquisition, the radar set is in track condition. The radar now sends target information to the computer in the CW radar system, which computes the intercept course to be flown. Target, aircraft steering, and missile launch information are presented to both the RIO and the pilot. During the course of the intercept (at the discretion of the pilot), the missile is launched at the target. Various phases of tracking are discussed in following paragraphs.

The normal track condition, which begins after the successful completion of a normal acquisition, is the most favorable condition for intercepting a target. At this time, the radar set is automatically tracking the target in angle and range (fig. 4-11). This information, along with aircraft steering and missile launch information, is displayed to both the pilot and the RIO. Since the information fed to the CW radar system computer is more accurate and complete than the information available during other tracking phases, the aircraft steering and missile launch information is accurate. Consequently, the possibility of a kill is greater.

If the target fades for a short time, the radar set maintains the track condition by continuing to track the position the target would reach, assuming that the range rate and angle rate were to remain constant. When the target reappears, the radar resumes normal track. All track information is displayed, even during the fade time, so that there is no interruption in the attack. If the target fails to reappear within 5 seconds, the radar automatically returns to search operation.

If, during normal track, a target starts jamming so the radar is prevented from continuing normal track, the system automatically switches to a home-on-jam (HOJ) condition. At this time, angle track is maintained on the jamming source in place of the target, and range track is maintained by operating on memorized range and range rate. Otherwise the intercept can continue in the normal manner for a successful kill. If the target return reappears on the indicator, the radar can automatically reacquire it to resume normal tracking. If this automatic action fails, the RIO can try to reacquire the target by pressing the lock-on switch to half action, setting the range strobe over the target with the radar control stick, and then pressing the lock-on switch to full action. If the radar successfully reacquires the target, normal tracking is resumed. If the reacquisition is not successful, the system switches to acquisition-on-jam (AOJ) operation.

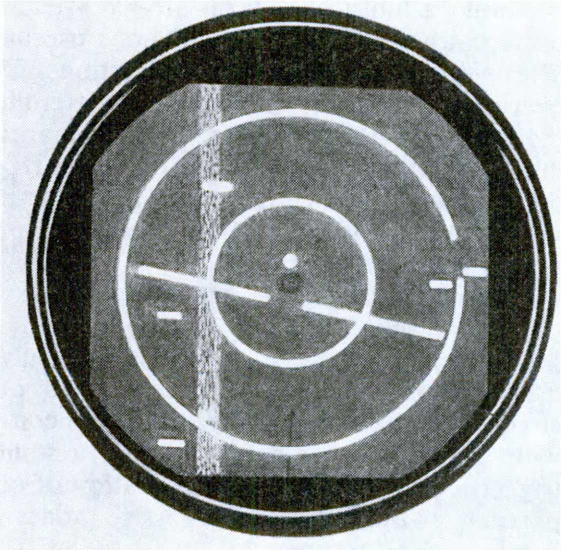

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Figure 4-11.—Radar presentation, normal track mode.

When the system switches to the AOJ tracking condition from HOJ, only angle information is available to the radar set. Therefore, only angle information is displayed. The pilot can guide the aircraft into position for a successful attack with the steering information provided; but display of the ideal range for launch is not available. Consequently, the pilot must decide the range at launch. If at any time during AOJ operation the target appears on the indicator, the RIO can try to acquire the target by pressing the lock-on switch to half action, positioning the range strobe over the target, and pressing the lock-on switch to full action. If the radar successfully acquires the target, normal tracking results. If the target still cannot be acquired, AOJ tracking resumes. At this time the RIO can decide whether to remain in AOJ, try to acquire again, or try manual track of the target.

The manual track capability lets the RIO track the target manually when automatic track is not possible. Angle and range information is generated by the radar and displayed to the pilot and RIO. The accuracy of the information is not as great as in normal track, but a successful attack and kill can be made.

After acquisition for manual track has been completed, the RIO checks the ANGLE LOCK light on the radar set control. If the light is on, indicating that the antenna servosystem is in automatic track, the RIO presses MAN Vc control to put the antenna under manual control (indicated by the ANGLE LOCK light going out). (Since the range strobe is not in coincidence with the target, angle track information is not gated into the antenna servosystem; consequently, the antenna would drift off the target if automatic angle track were maintained.) The RIO then adjusts the MAN Vc control to keep the range strobe at a constant distance from the target rather than directly over the target on the display because the strobe would obscure the target and make manual angle track more difficult. Then, the RIO must decide how to operate in manual track. The following alternatives are available:

- Continue as above, with aided range track and full manual angle track. This method is usually preferred in the absence of jamming.

- Operate with automatic angle track, achieved by pressing the MAN Vc control (ANGLE LOCK lamp lit). If there is any jamming, the system will angle track it. If there is no jamming, the RIO must first place the range strobe directly over the target in order to gate angle error information into the antenna servo circuits. If the range strobe is allowed to drift away from the target, the antenna servosystem will not receive any error information and the antenna might drift.

Polarization is effective in track as well as search. If weather or jamming interferes during any part of the track operation, the RIO can change the polarization of the transmitted energy to either linear or circular. The circularly polarized energy can be made to rotate in either direction.

If at any time during track, the RIO wishes to reject the target and return to search, the lock-on switch is pressed to half action and released. The radar automatically returns to the search pattern it was following when the track condition was initiated. The RIO can select another target at the same azimuth and elevation (visible in the B-sweep during track) without losing angle track. To do this, the lock-on switch is pressed to half action, the range strobe is positioned over the new target, and then the lock-on switch is pressed to full action. The radar then automatically acquires the new target.

THEORY OF OPERATION

The radar is composed of a number of functional subsystems. The transmitting system produces the pulsed RF energy which is radiated by the antenna to illuminate any targets in the area covered by the antenna pattern. The return from the targets is received by the antenna and sent to the receiving system by the duplexer. The receiver amplifies and detects the low power RF return energy and applies the resulting video signal to the display system for target observation and to the range and angle tracking systems during track operation. To maintain a constant target signal in the range and angle track systems, the receiver gain is controlled by the automatic gain control system. The display system provides the pilot and radar intercept officer with the information required to operate the radar and to fly the aircraft to achieve a successful interception. This information is derived from many sources. The range tracking system automatically determines the target range and range rate for use in the computer of the CW radar system in the computation of attack course and missile guidance data. The angle tracking system controls the antenna position to maintain target illumination and provide target bearing and line-of-sight rate, also required by the CW radar system. A program is developed for driving the angle search system in the antenna through the required search pattern. To stabilize the search pattern during aircraft maneuvers and to provide aircraft attitude information to the display system, the vertical reference system is required.

The following discussion of the theory of operation is arranged according to the various subsystems described above. It is not limited to the particular black box or chassis that contains the major position of that subsystem.

Transmitting System

The purpose of the transmitting system is to generate the RF energy that is radiated by the antenna to illuminate the area under search. The transmitter produces a high-power RF pulse, whose frequency can be preset to any value between the limits of 8,700 and 9,400 MHz. The pulse width can be either 2 or 0.4 microseconds. The width actually used is a function of the operating mode of the radar as determined manually by the operator, or automatically during the tracking operation. The pulse repetition frequency (PRF) is dependent upon the range selected and the width of the particular RF pulse that is being transmitted.

A synchronizing pulse, coincident in time with the RF transmitted pulse, is also supplied by the transmitting system. The synchronizing pulse is used as a zero time reference for all other circuits in the radar. During standby operation, with the transmitter not operating, a standby trigger is provided to permit operation of other portions of the radar in the passive modes and during ground testing.

Figure 4-12 is a block diagram of the transmitting system. You should refer to it while reading this section. When keyed with a

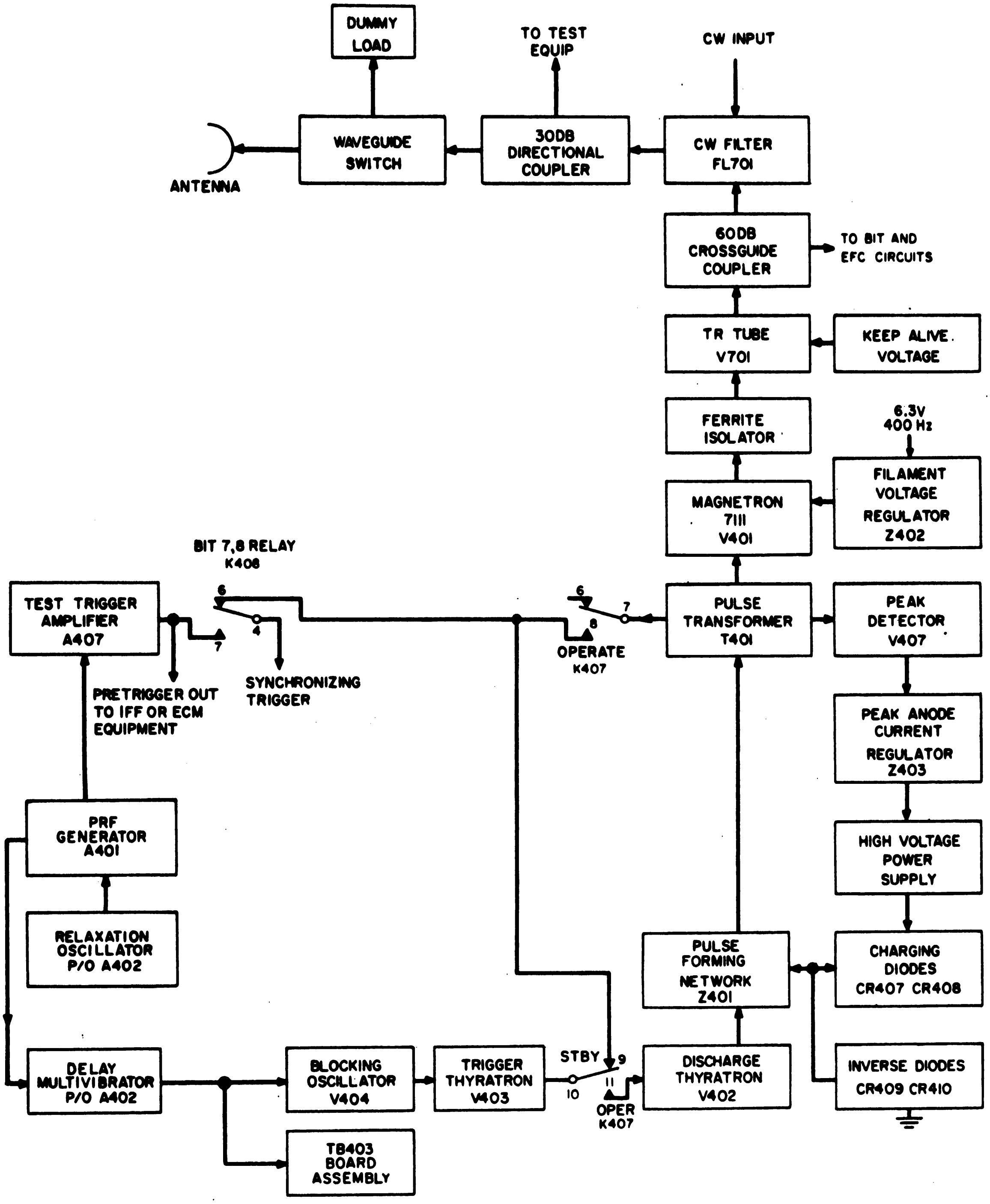

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Figure 4-12.—Transmitting system, block diagram.

high-voltage pulse from the modulator, the magnetron oscillates at the frequency determined by its cavity. In generating the required high voltage pulse, the high voltage power supply resonantly charges a pulse-forming network to approximately twice the steady dc voltage. The energy is stored in the network. When discharge thyratron V402 fires, it grounds one end of the pulse forming network, and the stored energy flows through the other end of the network to the primary of pulse transformer T401. The output of the transformer (stepped up 4:1) is applied to the magnetron.

The PRF generator determines the PRF at which the transmitter fires, but its output pulse does not have sufficient energy to fire the discharge thyratron directly. For this reason, the pulse is applied to trigger blocking oscillator V404. The output of V404 fires the trigger thyratron V403. The resulting high-current pulse from V403 ensures positive firing of discharge thyratron V402.

In order to maintain constant power out of the transmitter, it is necessary to regulate the peak anode current in the magnetron. In this system, current regulation is achieved by changing the voltage applied to the pulse-forming network so the amplitude of the input pulse to the magnetron is controlled. To do this, the peak anode current regulator (Z403) adjusts the output of the high voltage power supply. Any increase in amplitude of the magnetron current causes a proportionate change in the output of pulse peak detector V407, which acts on anode current regulator Z403 to reduce the 3-phase, 400-Hz input to the high voltage power supply.

The RF pulse width is determined by the pulse forming network Z401, which is actually a high-power delay line. When the network is discharged, a pulse travels down the line and returns (equal in magnitude but opposite in polarity), thereby discharging the line. The time required for this discharge is the output pulse width and is determined by the electrical length of the line. If there is an impedance between the network and the pulse transformer when the pulse-forming network is discharged, the return pulse on the network may be more negative than the initial pulse. The result is a residual negative charge on the network. On the next resonant charging cycle, the network would then charge to a higher potential than desired, and each succeeding cycle would, in turn, produce an even larger negative residual charge. The process would continue until some component in the loop is destroyed. To prevent this from happening, an inverse diode (CR409 or CR410) is provided, thus grounding out residual negative voltage on the network.

The temperature of the magnetron cathode must be held constant. When the system is turned on after a considerable off period, the required heating is supplied by the filament. As the magnetron continues to operate, the cathode current also furnishes heat. Since the current magnitude is somewhat fixed by the requirements of the system, a constant cathode temperature can be achieved only by reducing the heat contributed by the filament. When the system is in an operating mode, all filament voltage is removed from the magnetron because the average magnetron current alone is sufficient to provide full cathode heating.

The waveguide system performs a number of functions in addition to the transmission and reception of RF energy. These functions are described in the following paragraphs.

The ferrite isolator (fig. 4-12) connected between the magnetron (V401) and the antenna absorbs reflected RF energy during transmission, while permitting the transmitted energy to pass with little restriction. This reflected energy could distort the transmitted pulse and change the magnetron frequency.

The dual TR (V701) tube and its two adjoining hybrid junctions act as a switch to protect the receiver from transmitted energy. The TR tube is always maintained slightly below breakdown potential to provide for rapid ionization when the transmitted pulse appears. The resulting short circuit in the waveguide inserts attenuation in the path of the transmitted energy at the entry to the receiving system.

During transmission, filter FL701 couples the CW energy from the CW radar system to the antenna and prevents its entry into the receiving or transmitting circuits of the intercept radar. The filter presents a low insertion loss to the transmitted and received signals of the intercept radar.

The waveguide switch is provided to direct the transmitted energy into a dummy load during built-in tests. In normal operation, the dummy load is bypassed and the RF energy is passed to the antenna.

The RF energy is coupled through two rotary joints on the antenna gimbals before being fed to the feedhorn. These joints allow free movement of the antenna in azimuth and elevation to 120° without interfering with the transmission of the RF energy.

The RF energy from the feedhorn is concentrated and directed by the parabolic reflector of the antenna. The feedhorn is offset from the center axis of the reflector and is rotated by a spin motor so that the beam axis describes a conical path, and the RF energy is lobed in a pencil-shaped beam about the center axis of the reflector. When the radar set is not in operation, a shutter protects the receiver crystals from high power transmissions from other radars nearby. When the system is operating, the shutter is held open and passes RF signals to the receiver. When the system is turned off, the shutter closes automatically and attenuates all signals approximately 30 dB.

The antenna provides the means for radiating both pulsed and continuous wave signals and for receiving target echoes. It is mechanized so it can be either manually directed in azimuth and elevation or provide several types of automatic scanning motion. It also is capable of changing the polarization of the transmitted energy.

Normally, the energy transmitted to the antenna through the circular waveguide feedhorn is linearly polarized. Polarization refers to the orientation of the plane of electromagnetic oscillations as the wave progresses through the waveguide and through free space. During clear weather and in the absence of jamming signals, the linearly polarized transmitted energy produces effective target echoes. In rain or fog, both the transmitted pulses and the target echoes undergo attenuation. Similarly, linearly polarized clutter produce (by electromagnetic interference) the same effect as attenuation of transmitted and received energy from atmospheric causes. Whatever form the interference or clutter takes, it obscures the target returns.

Considerable improvement in radar performance can be realized by resorting to circular polarization of the transmitter output. Circular polarization is achieved by means of a polystyrene quarter-wave plate inserted in the feedhorn circular waveguide (fig. 4-13).

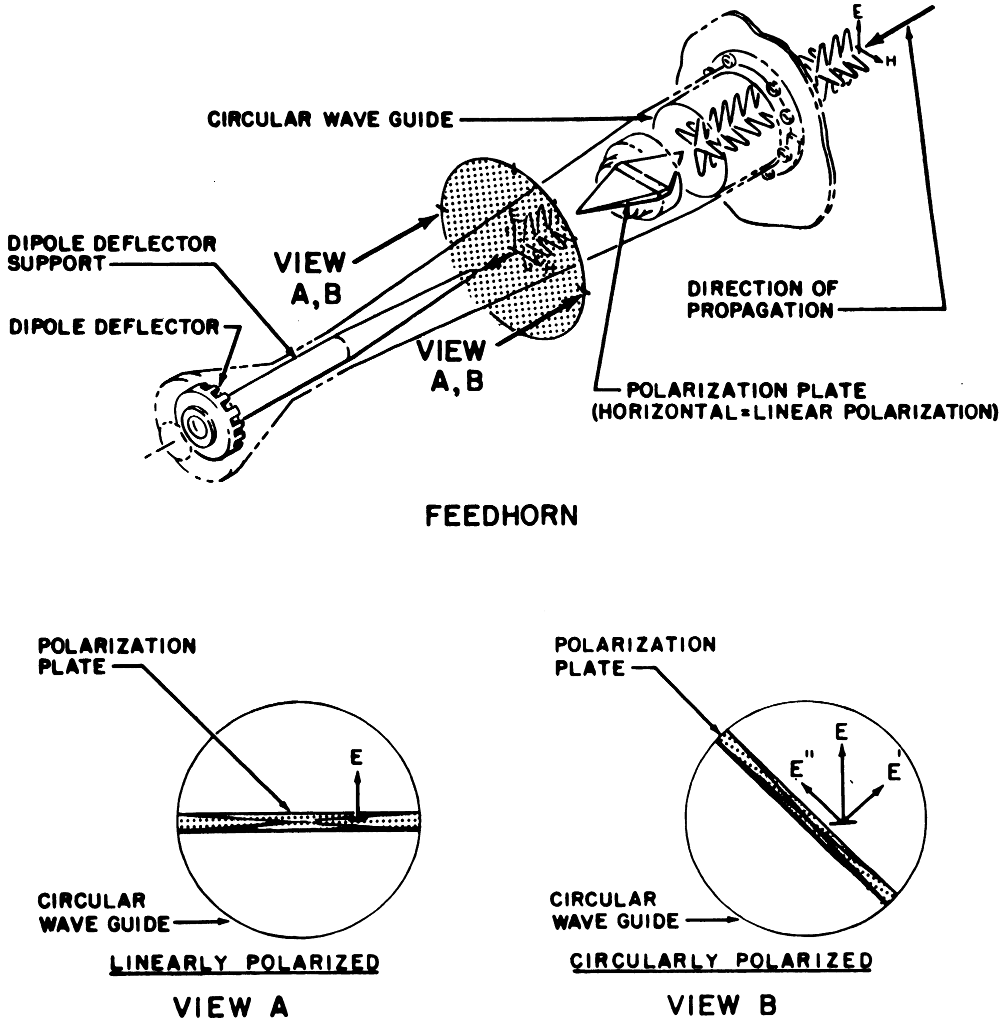

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Figure 4-13.—Circular and linear polarization.

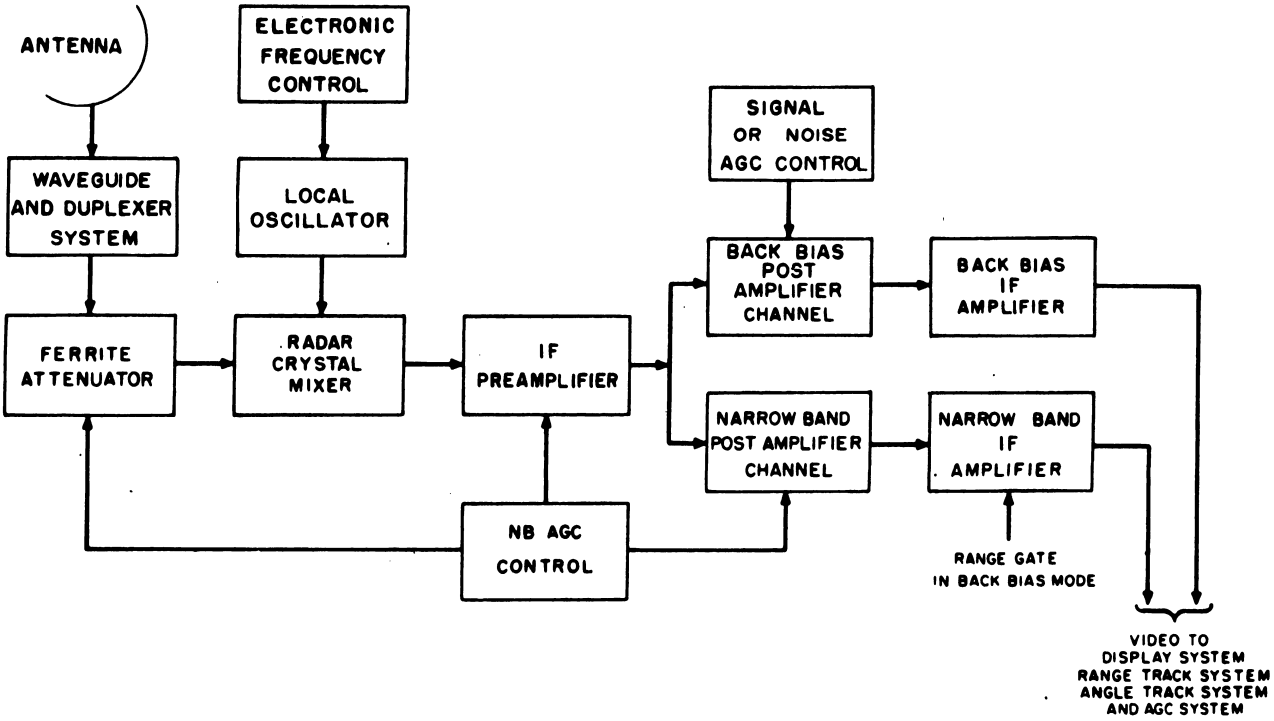
The speed of propagation of an electromagnetic wave is slower in higher dielectric materials than in air. Therefore, any portion of the transmitted wave that passes through the quarter-wave plate is slowed down. For the mode of polarization in use, the vertical E-field is concentrated at the center of the circular waveguide. Thus, when the plate is horizontal (as shown in view A of fig. 4-13) practically all of the energy passes perpendicularly through the plate and continues into space without change in polarization.

For circular polarization, the quarter-wave plate is rotated 45° on either side of the vertical. The vertical E-field intersects the plate at 45° and can be considered as resolved into two component fields: one in the plane of the plate and the other perpendicular to it. The component of the field in the plane of the plate passes through the quarter-wave length of the plate and is delayed by 90°. The perpendicular component of the field traverses only the relatively thin cross section of the plate, so that it is only slightly delayed. The result is that the two components of the field are 90° apart, and the recombined E-field rotates at a speed equal to the transmitted RF energy.

Circularly polarized target echoes are reformed by the plate into linearly polarized waves. Because its mount has a separate bearing, the quarter-wave plate is free to rotate independently on the feedhorn assembly, or it can remain fixed while the feedhorn is rotating. Control of the plate position is accomplished by the magnetic stop assembly, a cast ring clamped on the circular waveguide section. Two solenoids on the ring operate pawls that project through the waveguide wall. As the feedhorn rotates, bearing friction causes the plate assembly to rotate until it touches one of the pawls. It is held in that position by the rotational force of the feedhorn.

Receiving System

Refer to fig. 4-14 while reading the following paragraphs. The purpose of the receiving system is to receive the weak target signal return and to amplify the signal to a suitable level for use in the angle tracking, range tracking, and display circuits. Frequently, the target return is obscured by various forms of clutter, either from natural sources such as ground or cloud return or from unfriendly interference caused by jamming.


ANTENNA
ELECTRONIC FREQUENCY CONTROL
SIGNAL OR NOISE AGC CONTROL
WAVEGUIDE AND DUPLEXER SYSTEM
LOCAL OSCILLATOR
BACK BIAS POST AMPLIFIER CHANNEL
BACK BIAS IF AMPLIFIER
FERRITE ATTENUATOR
RADAR CRYSTAL MIXER
IF PREAMPLIFIER
NARROW BAND POST AMPLIFIER CHANNEL
NARROW BAND IF AMPLIFIER
NB AGC CONTROL
RANGE GATE IN BACK BIAS MODE
VIDEO TO DISPLAY SYSTEM RANGE TRACK SYSTEM ANGLE TRACK SYSTEM AND AGC SYSTEM

223.87

Figure 4-14.—Receiving system, block diagram.

A special back-bias receiving channel is used to provide target discrimination against certain of these clutter signals. Back-bias operation presents problems as it is not compatible with the high degree of receiver sensitivity required for maximum detection capability. For this reason, a second receiving channel is provided which does have maximum sensitivity. To achieve maximum sensitivity, a very narrow bandwidth is used; therefore, this channel is called the narrow-band channel. Selection of the particular channel can normally be made by the operator with the CLUTTER switch. There is one exception. If tracking was initiated in the narrow-band channel and the target amplitude is sufficient, an automatic transfer is made to the back-bias channel.

When a target is being tracked in the back bias-mode (heavy clutter), IF gating is used in the narrow-band receiver, which is used to provide the angle track information.

Echoes received by the antenna are passed through the waveguide and duplexer system and mixed with the output of the local oscillator to produce a 30-MHz intermediate frequency. The 30-MHz signal is detected by the mixer crystals and applied to the IF preamplifier. Here, it is amplified and sent to the postamplifier. When the signal enters the postamplifier, it is split into two separate channels: one channel supplies the narrow-band IF amplifier and the the other channel supplies the back-bias IF amplifier. The signals that enter the narrow-band channel of the IF postamplifier are coupled to the narrow-band IF amplifier. Here they are amplified and limited before application to the narrow-band filter. The signals are then detected and finally coupled to video amplifiers for use in the display, range tracking, and angle tracking systems. Likewise, the signals that enter the back-bias channel of the IF postamplifier are coupled to the back-bias IF amplifier, where they are amplified and detected. The output that results is coupled to the video amplifiers for use in the display and range tracking circuits during heavy clutter conditions or when the target returns exceed a preset threshold level.

The local oscillator is a reflex klystron which generates a signal 30 MHz above the radar transmitted frequency. The signal is mixed with the target return signal to produce the 30-MHz IF signal at the radar crystal mixers and the electronic frequency control (EFC) crystals. The 30-MHz frequency difference is maintained by the EFC circuit. The EFC circuit adjusts the local oscillator output frequency by changing the amplitude of the dc voltage applied to the reflector of the klystron. Manual tuning is also possible by mechanical adjustment of the klystron cavity.

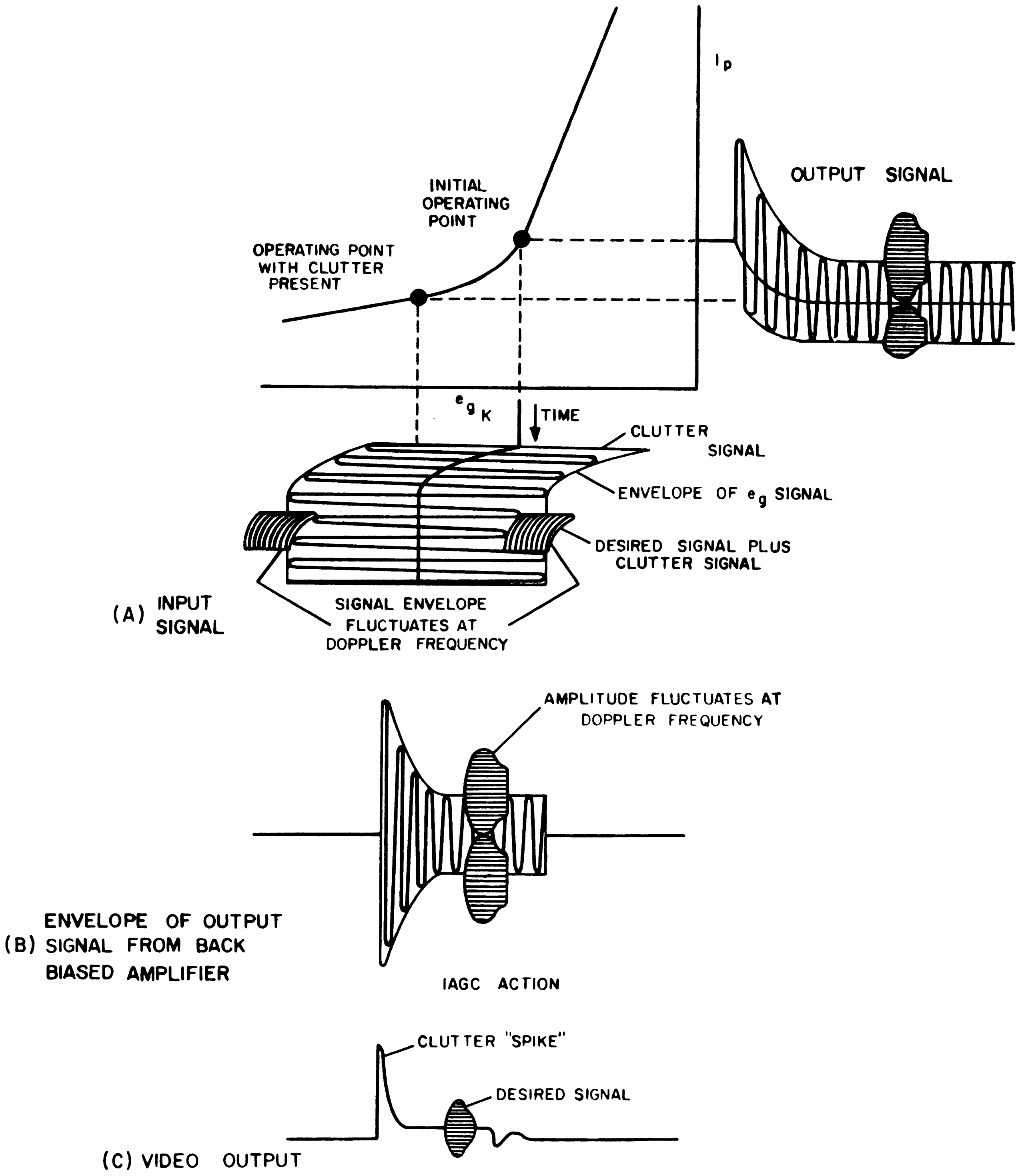
The IF preamplifier receives and amplifies the 30-MHz output of the crystal mixers and supplies the signal to the two channels of the postamplifier for further amplification. The gain of the receiver during track operation can be varied by applying AGC voltage to the grids of the first and third stages of the two post amplifier channcls. The narrow-band IF amplifier receives the output of the narrow-band channel of the postamplifier. The narrow-band IF amplifier consists of two wide-band amplifier stages, a limiter, a range gated stage, two narrow-band amplifier stages, a narrow-band filter network, a diode detector, and a video cathode follower.

During back-bias track operation, a gate timed to correspond to target range is received from the range tracking circuits of the synchronizer. Only the signals occurring during the time of the gate are coupled through the following stages.

The back-bias IF amplifier receives the output of the back-bias channel of the postamplifier. The back-bias IF amplifier consists of eight stages of IF amplification, a diode detector, and a video cathode follower. The back-bias IF amplifier provides a receiver channel of wide bandwidth and large signal handling capacity in order to improve target detection in the presence of clutter and jamming.

The back-bias amplifier stage incorporates values of cathode resistance which are higher than those normally found in conventional IF amplifiers. The stages also incorporate cathode bypass capacitors. The cathode capacitance, in conjunction with the tube characteristics, determines the delay time for immediate automatic gain control (IAGC); that is, self-acting automatic gain control within each stage. The IAGC operates in each stage of the amplifier in a manner which allows the amplitude of a desired signal to be constant whether or not an undesired signal is present. The output produced by a desired signal is the result of the step change in the envelope of the undesirable IF voltage when the desired signal appears. Figure 4-15 shows this action. The operating point of a back-bias amplifier stage is shown on the curve in view (A) of the figure. When clutter is applied to the tube, IAGC action reduces the clutter signal sharply by moving the bias point with a time constant determined by the value of the cathode capacitor and the tube characteristics.

The gain of a desired signal appearing in the presence of clutter will remain constant because



I_p
OUTPUT SIGNAL
INITIAL OPERATING POINT
OPERATING POINT WITH CLUTTER PRESENT
e_{gK}
TIME
CLUTTER SIGNAL
ENVELOPE OF e_g SIGNAL
DESIRED SIGNAL PLUS CLUTTER SIGNAL
SIGNAL ENVELOPE FLUCTUATES AT DOPPLER FREQUENCY
(A) INPUT SIGNAL
AMPLITUDE FLUCTUATES AT DOPPLER FREQUENCY
ENVELOPE OF OUTPUT
(B) SIGNAL FROM BACK BIASED AMPLIFIER
IAGC ACTION
CLUTTER "SPIKE"
DESIRED SIGNAL
(C) VIDEO OUTPUT

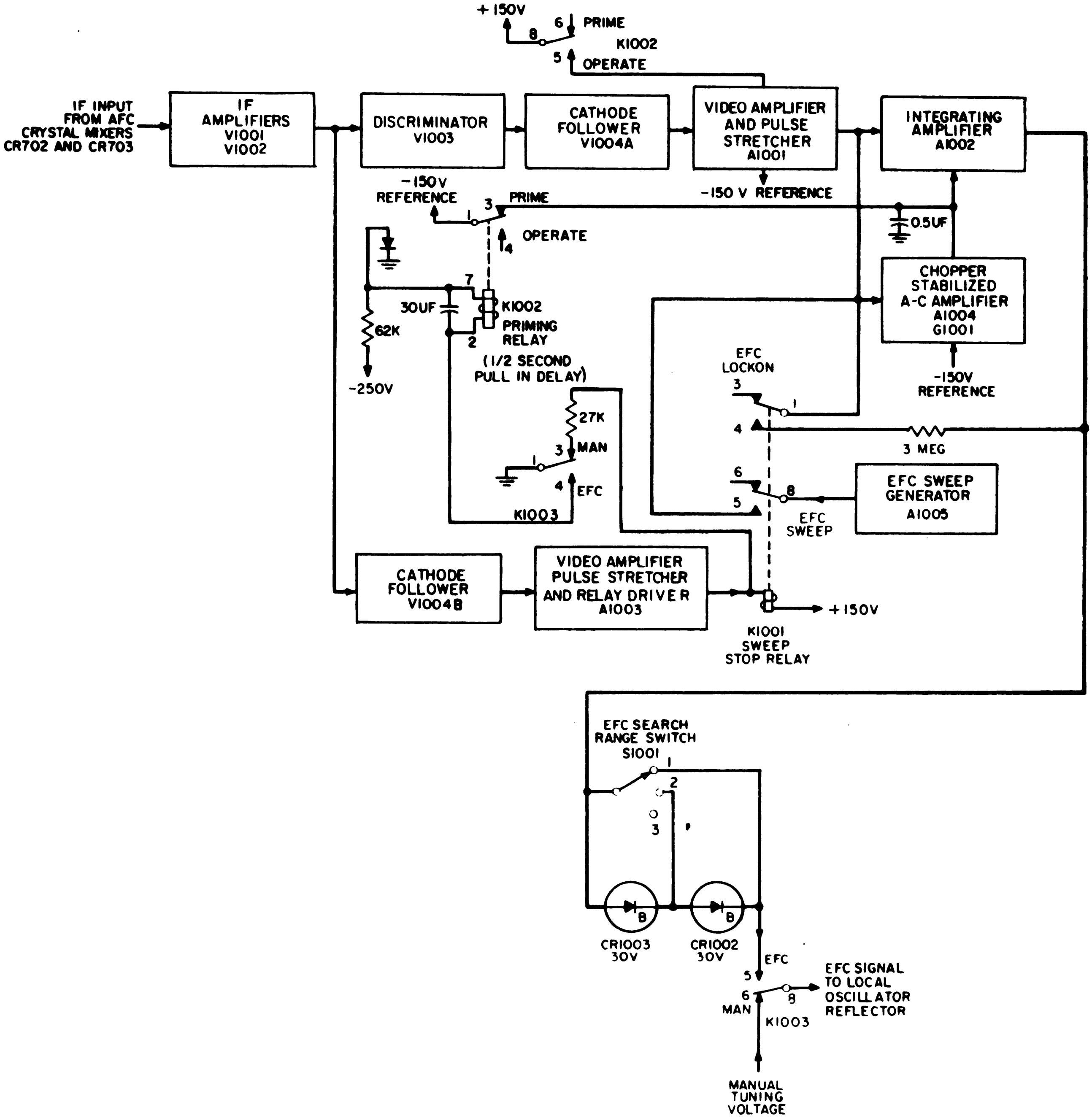
223.88

Figure 4-15.—Signals in back-bias amplifier.

of this back-biasing characteristic of the amplifier. The clutter signal and the target return cannot be phase-coherent as they differ by the Doppler frequency. Because of this, the idealized output signal from the stage appears as shown in view (B) of figure 4-15. The desired signal is shown after the voltage spike as a narrow fluctuating signal. The envelope of the signal from the back-bias IF amplifier stages, which fluctuates at the Doppler frequency, is shown in view C of figure 4-15.

The EFC performs two functions: It establishes the intermediate frequency (IF) of the system at the center frequency (30 MHz) of the receiver immediately after the transmitter is turned on, and it maintains the intermediate signal frequency within the passband of the receiver. These functions are accomplished by controlling the output frequency of the local oscillator, as was mentioned earlier in this chapter.

The EFC circuits are shown functionally in figure 4-16. You should refer to this figure while


+150V
6
8
PRIME
K1002
5
OPERATE
IF INPUT FROM AFC CRYSTAL MIXERS CR702 AND CR703
IF AMPLIFIERS V1001 V1002
DISCRIMINATOR V1003
CATHODE FOLLOWER V1004A
VIDEO AMPLIFIER AND PULSE STRETCHER A1001
INTEGRATING AMPLIFIER A1002
-150V REFERENCE
3
1
PRIME
OPERATE
4
-150 V REFERENCE
0.5UF
7
30UF
K1002 PRIMING RELAY
2
62K
-250V
(1/2 SECOND PULL IN DELAY)
CHOPPER STABILIZED A-C AMPLIFIER A1004 G1001
-150V REFERENCE
EFC LOCKON
3
1
4
3 MEG
27K
3
MAN
1
4
EFC
K1003
6
8
5
EFC SWEEP
EFC SWEEP GENERATOR A1005
CATHODE FOLLOWER V1004B
VIDEO AMPLIFIER PULSE STRETCHER AND RELAY DRIVER A1003
+150V
K1001 SWEEP STOP RELAY
EFC SEARCH RANGE SWITCH S1001
1
2
3
B
B
CR1003 30V
CR1002 30V
EFC
5
6
MAN
8
K1003
EFC SIGNAL TO LOCAL OSCILLATOR REFLECTOR
MANUAL TUNING VOLTAGE

223.89

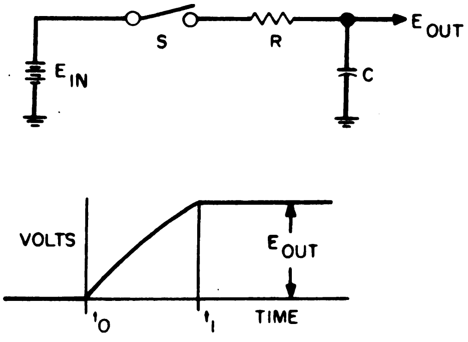
Figure 4-16.—Electronic frequency control circuits, simplified block diagram.

reading the rest of this section. A sample of the transmitted pulse is coupled to EFC crystals CR702 and CR703. The local oscillator output, 30 MHz above the transmitted frequency, is mixed with the sample of the transmitted pulse. The difference frequency signal resulting from the mixing is applied to IF amplifiers V1001 and V1002, where it is amplified to a usable level and applied to frequency discriminator V1003.

The discriminator circuit develops negative pulses when the frequency difference is above 30 MHz and positive pulses when the frequency difference is below 30 MHz. These are coupled to the video amplifier and pulse stretcher (A1001) through the cathode follower V1004B.

The pulse stretcher widens the pulse to approximately 300 microseconds long with an amplitude proportional to the frequency deviation from 30 MHz. When the difference frequency is above 30 MHz, the stretched pulse is negative, and when the difference frequency is below 30 MHz, the pulse is positive. These pulses are coupled to the integrating amplifier (A1002), depending upon the negative- or positive-going pulses from the pulse stretcher. The output of the integrating amplifier (A1002) is a negative voltage that is applied to the reflector of the local oscillator klystron to control the frequency of its RF output. This function closes the EFC loop.

Integrating amplifier A1002 develops a positive-going voltage for a negative-going input. An example of a simple passive integrator is shown in figure 4-17. When switch S is closed, capacitor C charges as shown. If switch S is now opened as shown at time t_1, the charge on C and hence E_{out} remains at the level achieved before switch S was opened. Integrating amplifier A1002 (fig. 4-16) operates in exactly the same manner as the passive integrator. The amplifier, in addition to inverting the output polarity, has the effect of multiplying the input signal and the time constant by the gain of the amplifier. In this way, a more nearly linear charging curve is achieved than that shown in figure 4-17. The reference center about which the dc voltage varies is established by a 150-volt reference potential from a voltage divider in A1001 (fig. 4-16). This level is preset prior to EFC search, so the search centers about 30 MHz.



223.90

Figure 4-17.—Simple passive integrator.

As stated previously, the EFC loop is closed when the frequency difference between the local oscillator output and the transmitted pulse is within the passband (approximately 25 to 35 MHz) of the IF amplifiers in the EFC control unit. For example, if the difference frequency is above 30 MHz, negative pulses are coupled out of the frequency discriminator. These pulses are fed into the video amplifier and pulse stretcher (A1001), where negative pulses are developed, proportional in amplitude to the frequency deviation above 30 MHz. The negative-stretched pulses are applied to integrator A1002, which causes the dc output to integrate to a less negative voltage. This voltage, applied to its reflector, drives the local oscillator to a lower frequency. Thus, the EFC circuit constantly adjusts the local oscillator frequency to compensate for changes in the magnetron frequency.

Automatic control of the receiver gain is required for normal operation of the range and angle tracking circuits. Signal level can be maintained for return signals varying in strength from 1 milliwatt down to one ten-thousand-millionth of a milliwatt.

The radar has two receiver channels: the narrow band and the back bias. The AGC system has capabilities for controlling the gain of both these channels. The back-bias receiver has two AGC control loops: the signal AGC and a noise AGC. The signal AGC is used to control the gain when a target is being tracked, and the noise AGC is used to provide gain control in a clutter environment or in the presence of certain types of jamming.

In addition to providing automatic gain control of the receivers, the AGC system performs the following functions:

- The AGC system detects target amplitude modulation (angle error signal) for use by the angle tracking circuits.

- The signal AGC (the output of which is a function of the target amplitude) derives its information from the target detector, and its output controls the operation of lock-on circuits in the range track system.

- The power level mode switch is controlled by the output of the narrow-band AGC. This output is proportional to the signal strength of the target being tracked. When this signal exceeds a predetermined level, the power level mode switching circuits are transferred from narrow-band to back-bias operation.

- One output of the noise AGC serves as the input for the HOJ-AOJ detector. When the noise AGC level exceeds a predetermined value, the radar automatically transfers to HOJ operation.

- Portions of the AGC circuits provide manual gain control in search.

Vertical Reference System

Figure 4-18 is a simplified block diagram of the vertical reference roll channel of a vertical reference system. The climb and roll channels operate in the same way; therefore, only the roll channel is described here. You should refer to figure 4-18 as you read this section.

In level flight, the gyro roll synchro transmitter output to the stator of roll control transformer B5003 is such that there is no voltage induced in the B5003 rotor. Thus, no voltage is applied to roll magnetic amplifier A4901. During aircraft maneuvers, relative motion between the gyro gimbals and the aircraft causes voltage proportional to the angles of displacement involved to be induced in the transmitting synchros. The output of the roll synchro transmitter is now such that the rotor of roll control transformer B5003 is no longer in the zero output position. As a result, there is a voltage applied to magnetic amplifier A4901. The signal is amplified in A4901 and applied to the roll servomotor (B5001). Roll servomotor B5001 drives the rotor of B5003 in a direction to minimize the output. B5001 also drives the gearbox and roll dial to indicate the amount of displacement. This action continues until the output of B5003 is zero. By this process, the roll dial and the roll shaft are deflected an amount proportional to the aircraft deviation from level flight in the roll axis. Simultaneously, the roll shaft positions the resolvers and induction potentiometers used for space stabilization in roll. The resolvers are so positioned so each may be considered a part of an individual subsystem. They are parts of the antenna stabilization subysystems, B-sweep subsystem, and artificial horizon line subsystem.

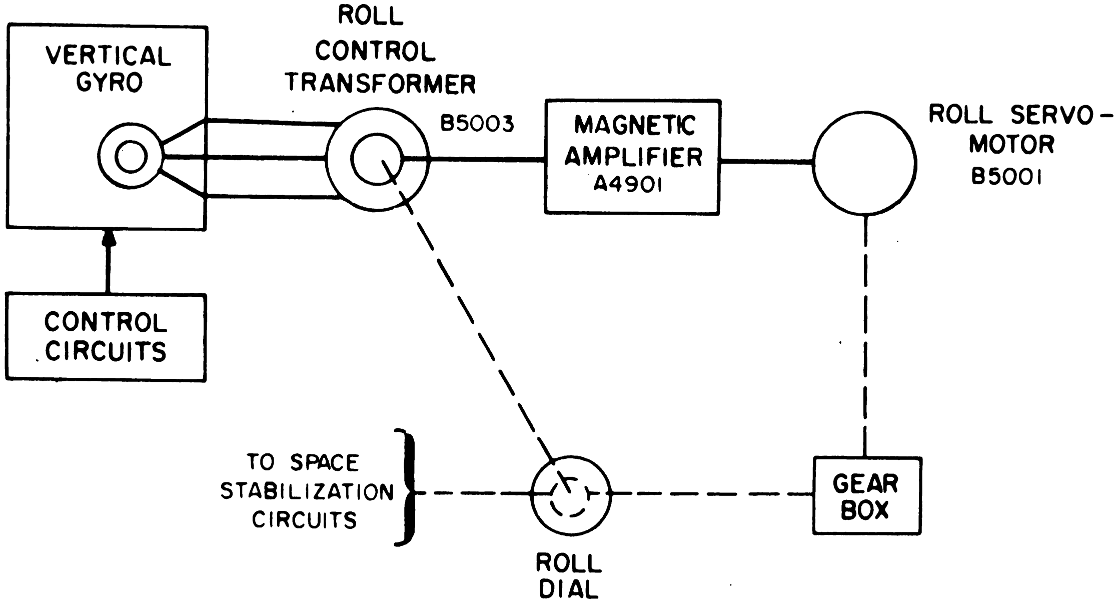


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Figure 4-18.—Vertical reference system, block diagram.

In straight and level flight, the principal axes of the vertical gyro are aligned with the aircraft so the roll axis is parallel with the longitudinal axis, the climb axis is parallel with the transverse axis, and the spin axis is parallel with the vertical axis. An erection system is provided to orient the gyro spin axis on a line passing through the center of Earth. Erection is to compensate for errors resulting from rotation of Earth, motion of the gyro with respect to Earth, and gyro drift.

The spin axis is oriented by gravity-sensitive devices. The gyros have a bubble-type electrolytic vertical-reference device mounted on the inner gyro gimbal. Displacement of the sensors mounted within the gyro causes the bubbles in the sensors to move off-center and applies corrective voltages to torque coils mounted along the climb and roll axes. The torque coils reposition the gyro gimbals until the spin axis is once more aligned with the gravitational field of the Earth. At this time, the sensor bubbles are centered and corrective torque removed.

The bubble-type electrolytic gravity sensors should be affected only by gravity for ideal operation. However, other accelerations, which result from aircraft speed changes or maneuvers, also affect the sensors. To avoid excessive erection errors, any maneuver sufficiently violent to produce excessive error in the sensors actuates a cutoff of error signal. The cutoff removes erection of excessive acceleration in the plane, placing the gyro in a state of free drift until the excessive acceleration is no longer present. The gyros have a cutoff in the roll plane only.

After prolonged maneuvers, the vertical gyro can drift sufficiently to cause an abnormal presentation upon return to normal flight. At such times, the radar intercept officer can hold the GYRO switch at FAST to rapidly restore the horizon line to normal. By this method, initial erection is applied to the torque motors for as long as the GYRO switch is held at FAST.

Mode and Track Switching Circuits

The mode and track switching circuits provide an automatic and a semiautomatic means of transferring the radar system from one mode of operation to another. The various modes of operation and the switching required for each mode are described in the following paragraphs.

SEARCH.—During search operation, the switching circuits provide an automatic antenna scan pattern and manual control of the range tracking system. The switching circuits also provide a search display on the indicators and allow the RIO to control and select the desired radar functions. The RIO selects the antenna scan pattern by means of switches on the radar set control and adjusts the azimuth and elevation coverage of the scan pattern with the radar control stick and the elevation control wheel on the antenna control. Also, the RIO can select the range displayed on the indicator, the receiver channel in use, and the type of polarization of the transmitted energy. During search, the switching circuits provide manual control of the radar receiver gain. The RIO adjusts the gain by means of a front panel control on the radar set control. When the system is in radar, boresight, or map mode and the range displayed is 10, 25, or 50 miles, an acquisition symbol is displayed on the radar indicator. The azimuth and range positions of this symbol are controlled by the radar control stick. The map mode is like the radar mode, except that the elevation coverage of the antenna is reduced and circular polarization (if selected) is removed. In the boresight mode, the switching circuits remove the antenna scan pattern and manual control of the antenna and point the antenna dead ahead to allow the pilot to conduct an optical attack in case of radar malfunction.

ACQUISITION.—Complete acquisition of a target by the radar system is possible only in the radar and map modes, and only in the AI ranges. In the boresight mode, it is possible to acquire a target in range only. The radar intercept officer starts the acquisition process in the radar or map modes by bracketing the target dot with the acquisition symbol and pressing the lock-on switch to half action. The lock-on switch initiates a relay sequence which transfers the antenna to manual control and provides a range strobe on the indicator B-sweep. When the range strobe and the acquisition symbol have been adjusted on the target, the RIO presses the lock-on switch to full action and the system attempts to lock on the target automatically. If a target is present within the tracking gate, the target detector and lock-on circuits detect the presence of the target and initiate a relay sequence which transfers the system to track operation. The affected relays remove the manual control inputs from the range and angle track systems and supply received target information to these circuits for automatic tracking. The relays also provide a track display on the radar indicator.

PILOT LOCK-ON MODE.—The pilot lock-on mode (PLM) provides the pilot with the ability to initiate target acquisition and lock-on. It also provides for his priority for control of the radar. PLM is initiated by the pilot pressing his target acquisition enable switch to half action. This commands the antenna to boresight and selects a 5-mile range B-sweep presentation on the indicator displays. Flying a pursuit course, the pilot presses the target acquisition enable switch to full action when he judges the target to be on boresight. After a short time delay, the full-action signal is transmitted to the synchronizer target detector and tracking circuits. Simultaneously, a range sweep strobe signal is generated that sweeps the range gate in the tracking circuits through the 5-mile range. When coincidence occurs in time between the range gate and the target video, range lock-on occurs, followed immediately by angle track. Target rejection is done either by the RIO or pilot by switching to half action momentarily.

TRACK.—After the target has been acquired, the system is in track operation, and it remains so until the target is manually rejected or until the target return is lost. During this time, the range track circuits provide target range and range-rate information to the computer for attack course computations. If the target return fades while the system in the radar mode, the lock-on circuits deenergize the relay that initiated the lock-on sequence. A time delay prevents the remainder of the relays from deenergizing until 5 seconds later. If the target reappears in the tracking gate during this 5-second period, the system resumes tracking. If the target does not reappear, the switching circuits transfer the system to search operation. If the target reappears outside the tracking gate during the 5-second period (target not at the same range as the range strobe), the RIO can reacquire the target without losing angle track by pressing the lock-on switch to half action, repositioning the range strobe over the target, and pressing the lock-on switch to full action. The system then reacquires the target in range. In normal radar track operation, the switching circuits also allow range track to be transferred to a target at a different range without placing the entire system in search. To do so, the RIO presses the lock-on switch to half action. If the system has been tracking, the range track circuits are transferred to manual control and the angle track circuits operate on memory. The RIO then positions the range strobe on the desired new target and presses the lock-on switch to full action. The system then reacquires the new target in the normal manner. When the interceptor-to-target range is less than that required for a successful engagement, the computer provides a breakaway signal to the switching circuits which cause a breakaway-X to be displayed on the radar indicator.

HOME-ON-JAM (HOJ).—If a target that is being tracked in the normal manner operates a noise or CW jammer that obscures the target return, the switching circuits automatically transfer the radar to HOJ operation. The jamming signal is detected by the HOJ/AOJ detector, which monitors the back-bias noise AGC and the CW signal level in the back-bias IF amplifier. A relay energized by the HOJ/AOJ detector transfers the system to HOJ operation, as shown by the HOJ light on the RIO indicator. The HOJ relay circuits are interlocked by the normal lock-on circuit to prevent HOJ operation if the target is not obscured by the jamming. The HOJ relay circuits transfer the range track circuits to memory operation to supply predicted range and range-rate information based on the last known range rate and range of the target. The angle track circuits automatically track the jamming signal in angle and provide this information to the computer. If jamming ceases during HOJ operation and the predicted range is at the correct value, the switching circuits automatically transfer the system back to normal tracking. If the predicted range is not correct when the system transfers back to normal operation, the system remains locked on for 5 seconds, allowing the operator to relock on the new target range. After 5 seconds, the radar unlocks and returns to search. Relock on the target can be attempted if target burn-through occurs and the system remains in HOJ operation. Relock from HOJ is the same as relock from normal track, except that the jamming signal might be present. If there is a jamming signal when the RIO presses the lock-on switch to half action, the angle track circuits continue to track the jamming signal while the RIO manually adjusts the range strobe on the target. When the target is acquired, the system transfers to normal tracking. If the target is not acquired, the system transfers to acquisition on jam operation, since the range memory is destroyed.

ACQUISITION ON JAM (AOJ).—If a jamming signal is encountered during search operation and the target return is obscured, acquisition and lock-on can be accomplished on the jamming signal to provide system angle tracking only. The presence of the jamming signal is detected by the HOJ-AOJ detector, allowing the AOJ relay to energize during acquisition. As a result, the system is in the AOJ tracking condition and angle tracking is established on the jamming signal. Since no target range information is received by the system, the range tracking circuits are not used during AOJ. If the jamming signal ceases during AOJ tracking, the switching circuits automatically transfer the system back to the search mode. Under certain conditions, it is desirable to prevent AOJ operation. For this result, the TRACK switch is set in the AOJ OUT position, so that the AOJ relay cannot be energized by the switching circuits.

MANUAL TRACK.—The switching circuits provide a means of tracking the target manually when the TRACK switch on the radar set control is set at MAN. At this time, range lock-on is not possible. When the lock-on switch is pressed to half action, the system is in complete manual control. The antenna is manually positioned to illuminate the target, and the range strobe is positioned at the desired target range. When the lock-on switch is pressed to full action, the system switches to manual track operation. In this condition, the angle track system remains under manual control and range-rate information is supplied by the MAN Vc potentiometer on the radar set control. This manual range-rate voltage is supplied to the computer and is integrated by the range circuits to provide range voltage changes. For adjustment of this control, the RIO observes the relative movement between the target video and range strobe on the indicator B-sweep. Automatic angle tracking can be attempted at this stage. For this purpose, the RIO positions the range strobe directly over the target and presses the MAN Vc control. A switch on this control provides the switching signal necessary to lock up the angle track circuits. The ANGLE LOCK light on the radar set control lights to indicate the switch position. In automatic angle track, the range strobe must be kept on the target at all times so that the angle track circuits can receive proper angle track information. Otherwise the antenna might drift off the target.

DATA LINK.—Circle-dot data link operation provides the capability for pursuit of a target that is beyond the operational range of the radar system. The target is tracked by a ground-based radar installation. Target position, direction of flight, and speed are compared with the position and speed of the interceptor at the same instant. This information is received and converted to analog form and is then displayed on the radar set by means of two symbols—the data-link circle and data-link dot. Data link operation makes it possible for the interceptor to approach the target closely without announcing its presence since it is not necessary for the interceptor radar to be transmitting at this time. Once the target is within the effective operating range of the fire control system, normal radar acquisition and tracking can be resumed. During data link operation, a 28-volt data link signal is sent to the indicator control to provide the relay switching necessary to present the circle-dot display. No other switching in the radar set is needed to provide data link operation.

SIDEWINDER EXTENDED ACQUISITION MODE (SEAM).—This mode of operation provides target designation information to the selected AIM-9 missile through the use of radar information. In SEAM operation, the missile head seeker may be slaved to the radar antenna when the radar set is in the track mode, and a circle-dot displaying this information appears on the radar indicators. This is accomplished by the visual target acquisition set (VTAS) in conjunction with relay switching in the indicator control. To acquire a SEAM lock, the seeker head must be within 3° of the radar antenna lock angle when the radar set is in the track mode, and the AIM-9 missile audio tone must be above a preset threshold. A SEAM dot and a circle representing 20° of angular displacement from boresight are displayed on the indicators after AIM-9 seeker lock-on. SEAM dot displacement from the center of the display indicates the seeker head angular displacement from boresight, but the dot displacement is only linear out to 10° (approximately 0.3 inches). Radar displays that are not present during the SEAM display are the data link circle and dot, ASE circle and dot, search and acquisition displays, and the break-X symbol. Relay switching in the indicator control disables the data link mode and removes the break-X display capability when in SEAM.

Range Tracking System

The range tracking system automatically determines the range separation between a particular target and the radar. In addition, the range tracking system selects the desired target for angle tracking from among other targets that happen to be at the same azimuth and elevation bearing but at different ranges (which could cause angle track on the wrong target).

The discussion of range tracking circuits presented in the following paragraphs is divided into three divisions.

1. The rudimentary tracking loop, which describes the fundamentals of range tracking operation.

2. The simplified range tracking operation, which establishes the tracking gate relationship.

3. The dual-channel tracking loop, which introduces the switching and time relationships that occur with the use of the narrow-band and back-bias amplifiers.

RUDIMENTARY TRACK LOOP.—The range to a target is determined by a precise measurement of the time it takes for the transmitted RF energy to travel to the target and return. Radar range is therefore proportional to time; for example, the time to travel 2,000 yards and return (1 radar mile) is 12.36 microseconds. However, since the range track output must be a dc voltage proportional to range, a means to relate time to voltage is required. The time modulator makes the following conversions:

- At the instant the transmitter fires, a trigger is sent to the time modulator to start the range sweep.

- For any time after t_o (fig. 4-19) the range sweep is at some definite voltage. For example, at 150 microseconds after t_o (24,580 yards), the range output is equal to 49 volts.

- The range sweep voltage is compared with the dc range voltage, and when the two are equal, the comparator generates a pulse.

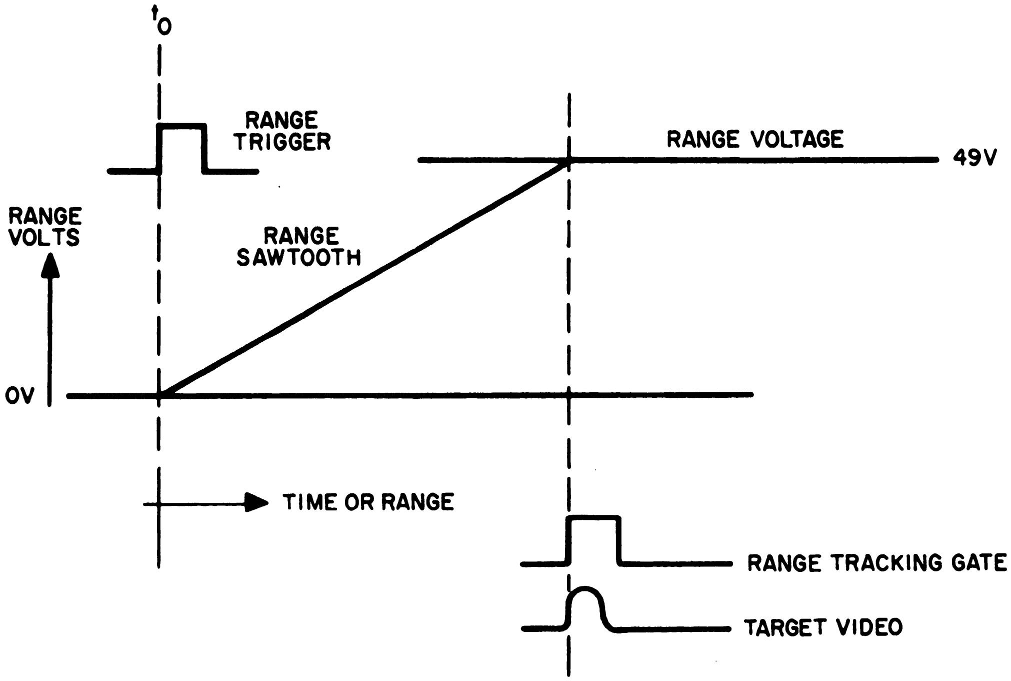

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Figure 4-19.—Development of tracking gate.

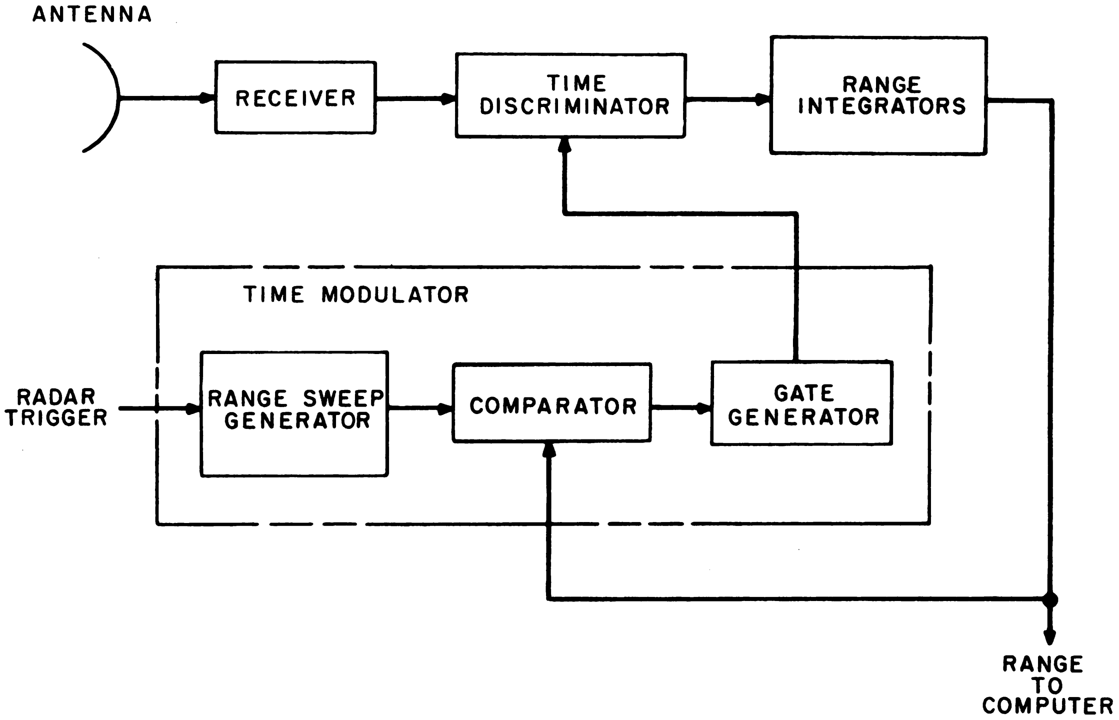

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Figure 4-20.—Rudimentary track loop, block diagram.

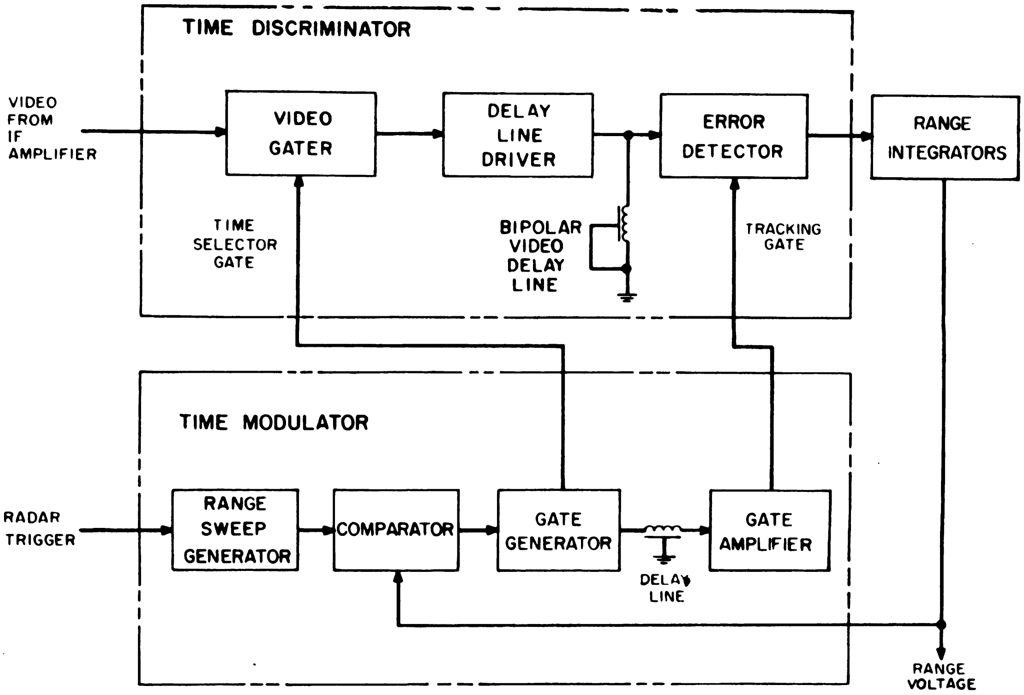

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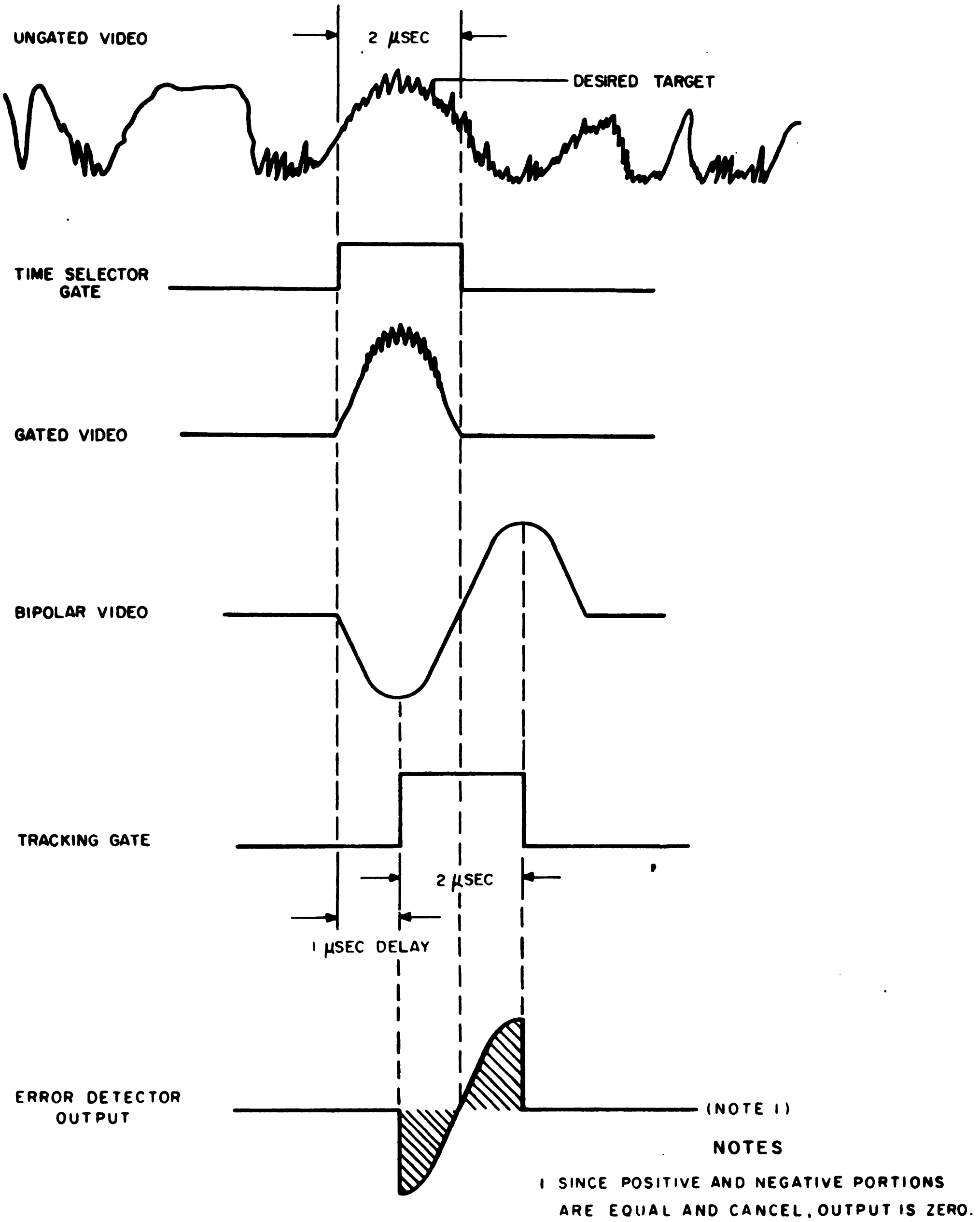
Figure 4-21.—Simplified range track operation, block diagram.

- This pulse is applied to the gate generator, which produces a tracking gate (fig. 4-20).

- The tracking gate is applied to the time discriminator, where it is compared in time with the actual video return from the target. If the range voltage is correct, the tracking gate arrives in the time discriminator at exactly the instant the target video arrives. If the range voltage, and hence the gate time position, is not exactly correct, there is an error in alignment between the tracking gate and the video return from the target. This misalignment produces an output from the time discriminator error detector, which is applied to the dc integrators to correct the value of the range voltage in order to reposition the range gate (tracking gate) to be precisely in time with the target video.

SIMPLIFIED RANGE TRACKING OPERATION.—The principles of operation of the time discriminator and the various gates are discussed in the following paragraphs. Figure 4-21 shows the time discriminator and the application of the selector gates. Refer to it as you read this section.

It is desirable to exclude extraneous returns such as clutter and jamming from the error detector. Only the video information present at the desired target position in range is sent to the error detector. By this means, undesired signals are prevented from affecting the tracking performance, except for the very brief period when the target is present. Exclusion of undesired signals is achieved by gating the video. This effect is shown in figure 4-22.



NOTES

1 SINCE POSITIVE AND NEGATIVE PORTIONS ARE EQUAL AND CANCEL, OUTPUT IS ZERO.

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Figure 4-22.—Video and error detector gate.

The error detector operates on bipolar video, generated by sending the video down a short-circuited delay line whose delay time is equal to the video pulse width. The original pulse is reflected, inverted, and delayed, as shown in figure 4-23.

Refer back to figure 4-21, the bipolar generator consists of a delay line driver and the short-circuited delay line. The error detector, which is gated, has an output proportional to the tracking error. Figure 4-22 shows the tracking gate perfectly aligned with the bipolar video, with the positive and negative portions of the bipolar video equal. Hence, the output of the error detector is zero. Figure 4-24 shows the tracking gate misaligned with the bipolar video. In this case, the tracking gate intercepts a larger portion of the positive part of the bipolar video than the negative, so there is a net positive output signal from the error detector for application to the range integrators.

As previously described, the error signal has the polarity to correct the range voltage and bring the output of the error detected back to zero.

The time selector gate, tracking gate, gated video, and bipolar video have a definite time relationship for a target 2 microseconds wide, assuming perfect tracking. This relationship is shown in figure 4-22. The 1-microsecond delay, produced by a delay line (fig. 4-21), is required for correct alignment of the tracking gate with the center of the bipolar video.

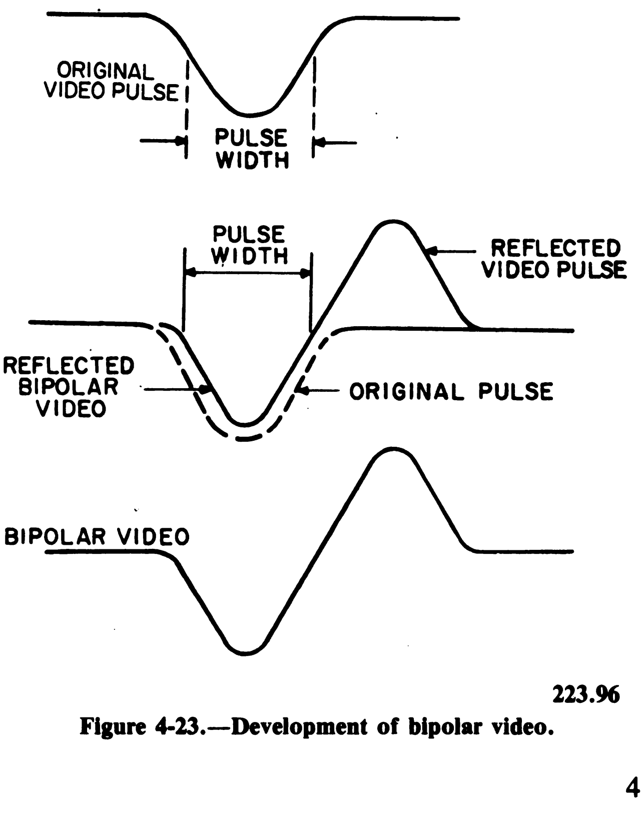

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Figure 4-23.—Development of bipolar video.

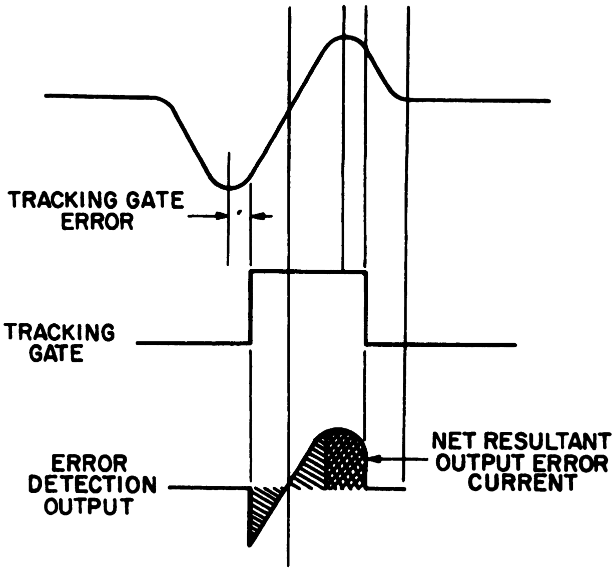

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Figure 4-24.—Misalignment of tracking gate and bipolar video.

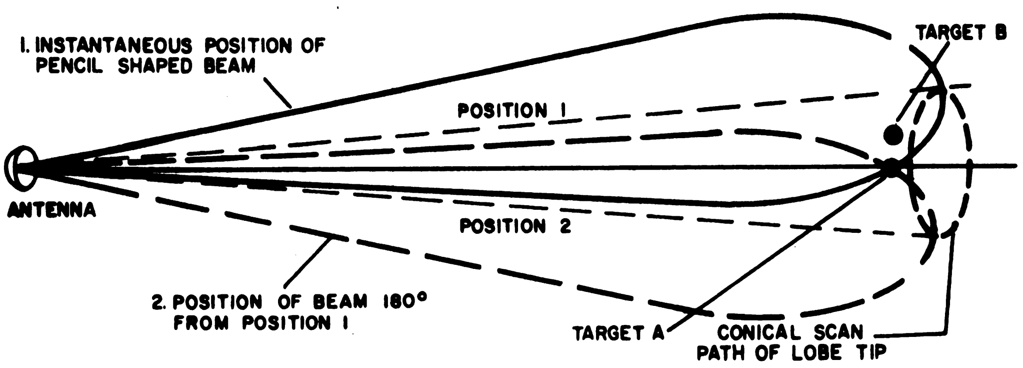
DUAL CHANNEL TRACK LOOP.—The dual channel range track loop receives video from either the narrow-band amplifier or the back-bias amplifier. The maximum detection and tracking range is obtained in narrow-band operation.

In narrow-band operation, a 2-microsecond pulse is transmitted; therefore, the video pulse to the range tracking circuits is 2 microseconds wide. In back-bias operation, the transmitted pulse is only 0.4 microsecond wide. Back-bias operation provides greater immunity to interference, but the back-bias IF amplifier operates on the return signal. This means that the target video is not a conventional, smoothly shaped pulse like the one from the narrow-band IF amplifier.

If tracking is initiated in the narrow-band channel, and the signal return exceeds a predetermined level at which tracking may be maintained in the back-bias channel, the range tracking system automatically transfers to back-bias operation, with the advantage of immunity from interference. The transfer operation is controlled by the power level mode switching circuits.

Angle Tracking System

The purpose of the angle tracking system is to maintain the radar antenna pointed at the desired target. Target bearing and angular rate


I. INSTANTANEOUS POSITION OF PENCIL SHAPED BEAM
TARGET B
POSITION I
ANTENNA
POSITION 2
2. POSITION OF BEAM 180° FROM POSITION I
TARGET A
CONICAL SCAN PATH OF LOBE TIP

223.98

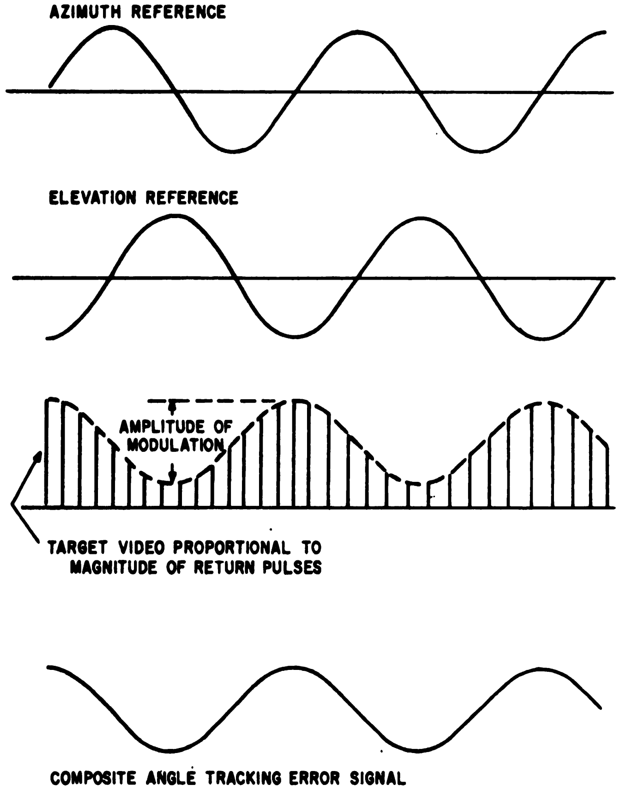
Figure 4-25.—Conical scan pattern.

(with respect to the aircraft) are provided to the computer of the CW radar system. Target position is also presented to the radar intercept officer and the pilot by means of the display system. When the antenna is thus oriented, it can illuminate the target with the CW RF energy required to guide the Sparrow III missile.

In normal operation, the angle tracking system uses the conventional pulse-radar angle-tracking scheme with conical scanning. However, when certain forms of jamming signals are transmitted by the target aircraft, the angle tracking system automatically continues tracking, using the jamming signal itself to provide the required target information. In the following presentation of the general theory of the angle tracking system, the basic idea of angle track operation is first considered; a rudimentary angle track loop is then discussed; and finally the complete angle track loop, as actually encountered in the intercept radar, is presented.

BASIC ANGLE TRACK OPERATION.— In order to obtain target position information, the radar antenna feedhorn is positioned slightly off-center and rotated at approximately 3,600 rpm. The mechanical offset causes the direction of the pencil-shaped radar beam to deviate slightly from the antenna centerline, and the rotation of the feedhorn causes the beam to rotate as shown in figure 4-25. This rotation is called nutation. The resulting pattern is called conical scanning. Any target along the centerline of the pattern (such as target A in figure 4-25) receives uniform radar illumination as the beam rotates. Consequently, return energy from target A is of constant amplitude; that is, there is no amplitude modulation.

Any other target (such as target B in figure 4-25) receives maximum illumination when the beam is directed toward it (position 1) and minimum illumination when the feedhorn has rotated 180° from this position (position 2). The return energy from this target is amplitude modulated in accordance with the lobing pattern of the radar beam. The amplitude of the modulation is proportional to the angular deviation from the centerline (angle error), and the phase of the modulations is related to the position of the target with respect to antenna coordinates. Figure 4-26


AZIMUTH REFERENCE
ELEVATION REFERENCE
AMPLITUDE OF MODULATION
TARGET VIDEO PROPORTIONAL TO MAGNITUDE OF RETURN PULSES
COMPOSITE ANGLE TRACKING ERROR SIGNAL

223.99

Figure 4-26.—Target video waveform.

shows this target video as detected in the radar receiver. The modulation shown is 180° out of phase with the elevation reference signal representative of a target directly above the antenna centerline, like target B in figure 4-25. This modulation is then detected to produce the composite angle track error signal and applied to the angle track circuits, which resolve the error signal into its azimuth and elevation components. These components are applied to the antenna drive circuits to reposition the antenna so as to eliminate the error. For the example shown in figure 4-26, a resultant output is obtained in the elevation channel of the track demodulator. This output is the antenna command signal that drives the antenna upward toward alignment with the target.

The detected amplitude modulation of return pulses is the composite angle tracking error signal. It is the input to the angle tracking system. The composite angle tracking error signal is demodulated with respect to the horizontal and vertical reference voltages as shown in figure 4-26. The reference voltages are obtained from the reference generator rotated by the antenna feedhorn spin motor. The angle track demodulator circuits resolve the error into azimuth and elevation antenna drive signals.

RUDIMENTARY ANGLE TRACK LOOP.—A block diagram of a rudimentary angle tracking circuit is shown in figure 4-27. The RF return energy, modulated as a function of the tracking error as described previously, is received by the antenna and sent to the receiver. The receiver detects the amplified signal to produce a video output. The video is then gated at the target range so that only the modulation from the desired target is applied to the angle track circuits. The gated video is then stretched to approximately 100 microseconds and applied to the boxcar demodulator, which derives the composite tracking error signal from the amplitude modulation on the video. This output is filtered to remove extraneous switching transients and is applied to the tracking amplifier.

The output of the tracking amplifier is sent to the azimuth and elevation coordinate demodulator. The two-phase output of the reference generator, which indicates the instantaneous position of the antenna feedhorn, is applied to the demodulators. The composite tracking error signal is demodulated with respect to the reference generator output, so that the target error position in azimuth is obtained from the output of the azimuth demodulator and the elevation target error from the output of the elevation demodulator. The demodulator outputs are applied to the azimuth and elevation amplifiers, which, in turn, are connected to the antenna drive circuits for each channel. Magnetic amplifiers in the antenna drive circuits control the hydraulic servo valves that control the hydraulic actuators

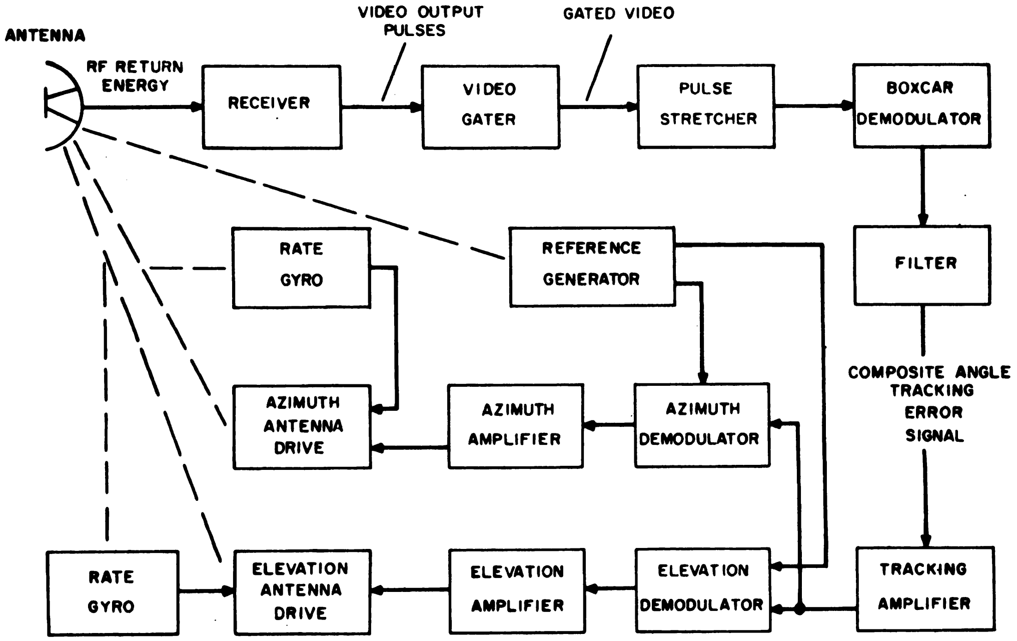


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Figure 4-27.—Rudimentary angle track system, block diagram.

on the antenna gimbals. To stabilize the gain of the antenna drive circuits and provide space stabilization of the angle tracking loop, rate gyro feedback is provided around the antenna drive.

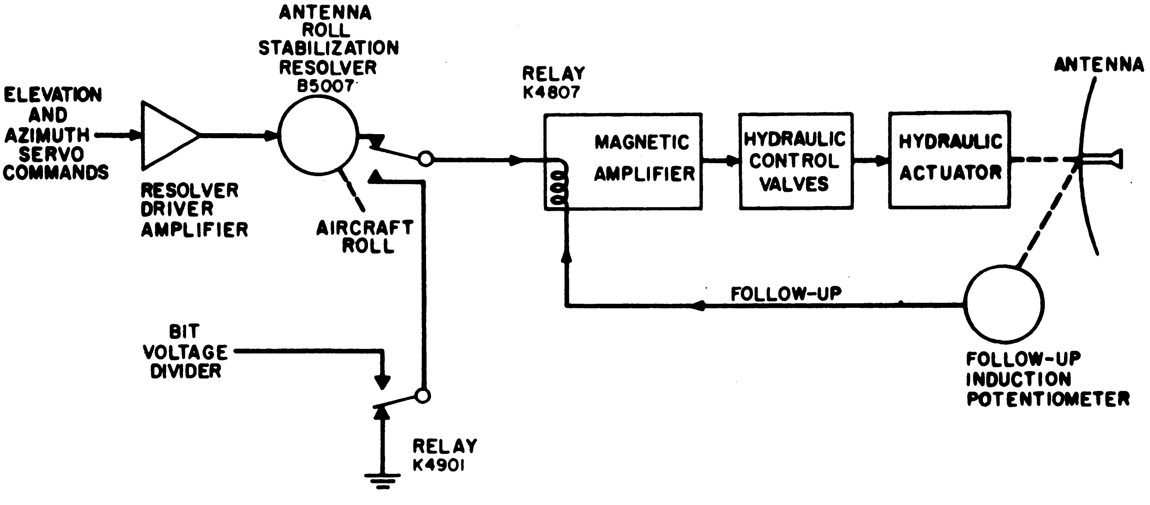
COMPLETE ANGLE TRACK LOOP.—The angle track stabilization loop consists of the antenna drive circuits and the rate gyro feedback. The purpose of the stabilization loop is to isolate the angle track system from motion of the interceptor. The main tracking loop has a relatively slow response in order to provide noise-free tracking. However, if the interceptor were to engage in any rapid maneuver, the main tracking loop would not be capable of responding to the resulting error signal in time to prevent loss of the target. It is at this stage that the rate gyros come into play. The disturbance introduced by the aircraft maneuver represents an increase in the rate of motion of the antenna in space. Since the rate gyros develop outputs proportional to the rate of antenna motion, the change in motion causes the rate gyros to produce error signals that tend to drive the antenna in the direction to maintain the desired tracking rate for the target.

For example, if an intercept run is being made on a target at the same altitude as the interceptor, the rate of motion of the antenna in elevation (commonly called line-of-sight elevation rate) is zero. Consequently, the commanded rate from the integrator and the actual rate of the antenna are both zero. If, however, the aircraft pitches upward (tending to pull the antenna off the target), a line-of-sight rate is introduced into the rate gyro which is compared with the zero commanded line-of-sight rate. The resulting net error signal is applied through the magnetic amplifier to the antenna hydraulic circuits. This drives the antenna down at such a rate as to cause the actual line-of-sight rate of the antenna to remain at zero and thus maintain tracking of the target.

The angle track system has three modes of operation: narrow band, back bias, and homing-on-jam (HOJ). In all modes of operation, the angle tracking signal is derived through the narrow-band receiving channel. The difference between the narrow-band tracking mode and the back-bias tracking mode is in the method by which the target gating or target selection is made. If the radar is operating in the presence of certain types of jammers, the IF gating breaks up the jamming signal into discrete pulses that can then be detected by the rest of the tracking circuits in the same manner as for the conventional target return. The angle track circuits then immediately begin to track the source on the jamming. If the jammer is turned off in an attempt to confuse the radar, normal tracking is resumed.

Angle Search System

The angle search system consists of the antenna positioning circuits, the servo command circuits, and the servo space stabilization circuit. As mentioned earlier, the angle search system is made up of antenna positioning circuits, servo command circuits, and a servo space stabilization circuit. Each of these circuits has an azimuth and elevation channel. The azimuth antenna positioning servosystem is identical with the elevation antenna positioning system, except for the command inputs. A functional block diagram of the circuit for one channel is shown in figure 4-28,


ANTENNA ROLL STABILIZATION RESOLVER B5007
ELEVATION AND AZIMUTH SERVO COMMANDS
RESOLVER DRIVER AMPLIFIER
AIRCRAFT ROLL
RELAY K4807
MAGNETIC AMPLIFIER
HYDRAULIC CONTROL VALVES
HYDRAULIC ACTUATOR
ANTENNA
FOLLOW-UP
FOLLOW-UP INDUCTION POTENTIOMETER
BIT VOLTAGE DIVIDER
RELAY K4901

223.101

Figure 4-28.—Antenna positioning circuit, functional block diagram.

and you should refer to it while reading this section.

The purpose of the antenna positioning servosystem is to direct the antenna so that a particular area in which targets are sought is illuminated. The area selected is determined by an automatically programmed scan pattern, or manually by the radar intercept officer, or from the ground in data link operation.

The automatically programmed scan pattern is commonly identified with the search mode of operation. In this mode, the system is used to locate a target that can subsequently be locked on and tracked. The search pattern is a three-bar Palmer scan with a retrace on the center bar.

In data link operation, the antenna positioning operates in the same way as narrow scan; however, the data link channel, instead of the radar intercept officer, commands the position of the search pattern sector.

The RIO can point the antenna dead-ahead; that is, at zero azimuth and elevation. This mode of operation is used when the tracking radar is inoperative, and it is desired to launch a missile optically. The aircraft is then flown on a pure pursuit course to maintain target illumination for missile operation.

The command signal in the antenna positioning system, and hence the resulting antenna orientation, is space stabilized. As a result, if the antenna is positioned so that a target is detected while the aircraft is flying straight and level, the antenna continues to be directed to the same position in space and the target continues to be observed. This will happen even though the aircraft is being put through extensive maneuvers.

Only the azimuth channel is discussed here. The desired antenna position is established by the command circuit, and the actual antenna position is determined by the induction follow-up potentiometer. The antenna command and follow voltages are both 400-Hz common phase signals. These signals are compared in the control winding of the magnetic amplifier. The difference between them is representative of the angular error between the desired antenna position and the actual antenna position. The error signal is amplified by the magnetic amplifier to provide sufficient power to operate the hydraulic valve on the antenna.

The servo valve, in turn, controls the hydraulic pressure to the hydraulic actuator. This drives the antenna gimbal in such a direction as to nullify the error signal, thereby placing the antenna at the desired command position.

Display System

The display system of the intercept radar presents the information required by the radar intercept officer and the pilot to successfully complete an airborne intercept with the Airborne Missile Control System (AMCS). The radar return is displayed so that the target aircraft can be detected and acquired for automatic tracking. Once the radar is tracking the target, additional information required by the pilot to steer the aircraft and launch the missiles is presented on the display screen. Upon missile launch, the pilot is provided with the necessary information for maintaining target illumination to provide CW guidance for the missile.

The radar display system is also capable of operating in conjunction with ground-based radar installations and displaying information received by a digital data communications set. The display data link symbols provide information as to the range, bearing, and altitude of the distant target. It also directs the pilot on the course required for an intercept. Once the target is within the operating range of the radar and fire control system, the pilot can switch back to normal radar operation in order to complete the intercept.

The A-gun channel, B-gun channel, and optical sight are the three independent channels of the display system. They are functionally discussed in this section. The first two channels present search and tracking information to the pilot and radar intercept officer in the form of symbols generated electronically and presented on the screen of a display tube. The optical sight, however, is a mechanical-optical system that enables the pilot to visually intercept a target aircraft or bomb a fixed target.

The A-gun channel presents tactical and attack information, while the B-gun channel is used to display the B-type radar presentation for target detection, acquisition, and tracking. A ground mapping display (also presented by the B-gun channel) is available in the form of a B-type presentation. The presentations of the A-gun and B-gun channels are both displayed on the screen of the same direct-view storage tube (DVST). Except for sharing the same viewing screen, the two channels operate independently. Therefore, they are discussed separately. The optical-sight system provides a fixed reticle with angle depression control for optical attack and delivery techniques of the low altitude bombing system (LABS).

COMPONENTS OF THE DISPLAY SYSTEM.—The display system consists of all the elements that directly contribute to the presentation displayed on the indicators. Signals are obtained from the climb and roll servos, antenna, range track system, receiver, and other components of the AMCS. The indicator control develops symbols, control voltages, and switching gates to convert the information received into the voltages required by the indicators. The RIO indicator contains a direct-view storage tube to display A-gun and B-gun channel information. The DVST is capable of presenting a persisting display of the entire area being scanned by the radar antenna. A target embedded in noise can be detected on the DVST display, since the target return is illuminated in the same position during each sweep of the antenna. However, the noise, which is random, usually does not appear in the same spot twice. The pilot's indicator also provides A-gun and B-gun channel radar displays. This differs from the RIO indicator which incorporates the optical sight system. The two indicators also contain power supplies, control circuits, and video amplifiers for the display tubes.

INFORMATION DISPLAYED.—The information displayed varies according to the operating condition of the radar. In search, many targets may be present on the display. In acquisition one particular target is selected for attack. In track, the information includes aircraft guidance and attack directions. Accordingly, the information displayed is discussed separately under conditions of search, acquisition, and track operation.

Presentations during search are the composite A-gun and B-gun radar displays on the direct-view storage tube and the optical sight display. The A-gun and B-gun composite search display (fig. 4-29) consists of a B-type presentation

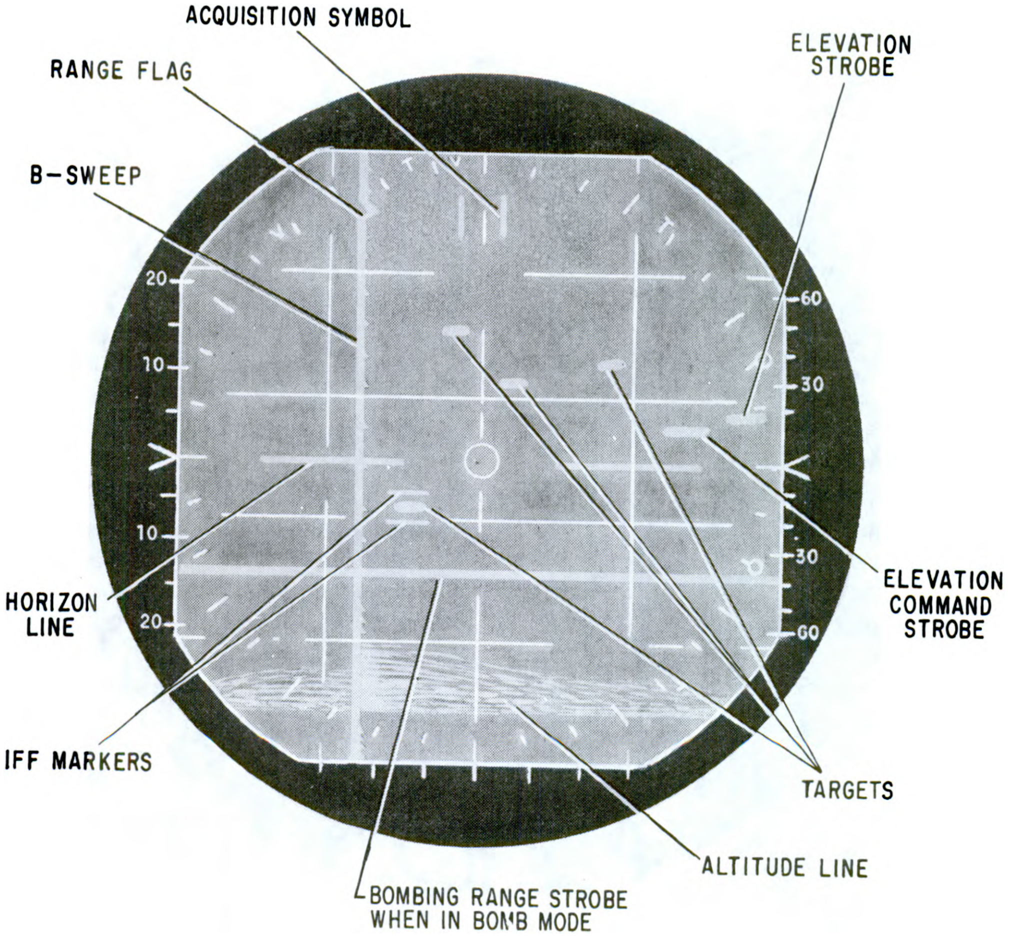


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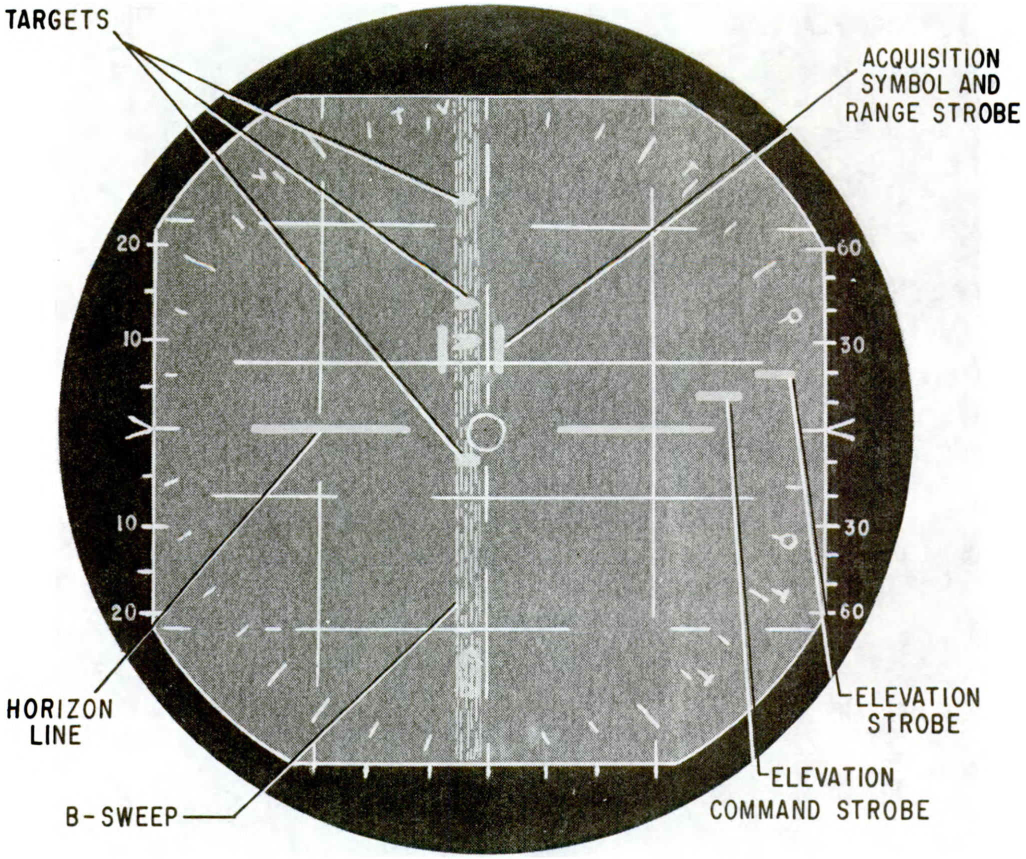
Figure 4-29.—Composite A-gun display, search presentation.

(range versus azimuth), a horizon line, an elevation strobe, and a radar acquisition symbol.

The type B presentation continuously displays radar target returns of the area covered by the antenna beam. The length of the two lines that make up the acquisition symbol indicates which range has been selected. The lines of the symbol appear approximately 1/8 inch long on the 5- and 50-mile range and 1/4 inch long on the 10- and 25-mile range. The range selection function is built into the radar control stick so that the RIO will not need to release his grasp on the radar control stick while attempting to acquire a target.

The azimuth position of the B-sweep on the B-gun display is determined by the antenna position with respect to the longitudinal axis of the aircraft. It is measured in a plane parallel to the earth's surface. The vertical sweep signal is obtained from a sweep generator in the indicator control and is synchronized with the radar transmitter. Target information obtained from the radar return signal is amplified in the radar receivers and video amplifiers; and the targets are displayed as blips of light on the B-gun display at their respective range and bearings. Vertical distance on the display screen, measured from the baseline, is proportional to target range. Horizontal distance on each side of the center is proportional to the azimuth bearing of the target, with respect to the longitudinal axis of the aircraft.

Acquisition is the process by which a target is selected and acquired for automatic tracking. When the desired target has been selected, it is then bracketed by the acquisition symbol and the lock-on switch on the radar control stick is pressed to the half-action position. The antenna, which now operates under manual control, slews to the azimuth position of the acquisition symbol as indicated by the position of the B-sweep in figure 4-30. The range strobe appears as an intensified spot on the B-sweep during acquisition



223.103

Figure 4-30.—Composite A-B gun display, acquisition presentation.

and track. This provides a more precise range indication than is possible with the acquisition symbol alone. The strobe is centered between the bars of the acquisition symbol, and the positions of both the strobe and the acquisition symbol are controlled by the radar control stick. The symbols are positioned in range by the forward movement of the radar control stick and in azimuth by the lateral movement of the stick.

When the lock-on switch is pressed to full action, the range tracking system attempts to lock on the selected target. The presentation remains unchanged until lock-on is achieved, at which time the track presentation described in the following paragraph is displayed.

When the RIO succeeds in locking on a target, the operation of automatic tracking is initiated. The acquisition symbol is removed from the display, but the remaining symbols (discussed previously) maintain the same functions as in the search and acquisition presentations. Several symbols, unique to the track condition, are presented on the radar display. These symbols include the range-rate circle, the allowable steering error (ASE) circle, the aim dot, and the R_a and R_{min} strobes. In addition, when the range strobe and target fall below the level of the R_{min} strobe, the track presentation is removed from the display screen and the breakaway-X symbol appears. The elevation command strobe is present in track to allow the RIO to see where in elevation the antenna will point after the system is returned to search or acquisition. The composite A-gun and B-gun track presentation is shown in figure 4-31.

GENERAL DESCRIPTION OF THE A-GUN DISPLAY.—The symbols generated in the A-gun channel are listed below.

1. Search and track operation
   - Horizon line
   - Elevation strobe
   - Elevation command strobe

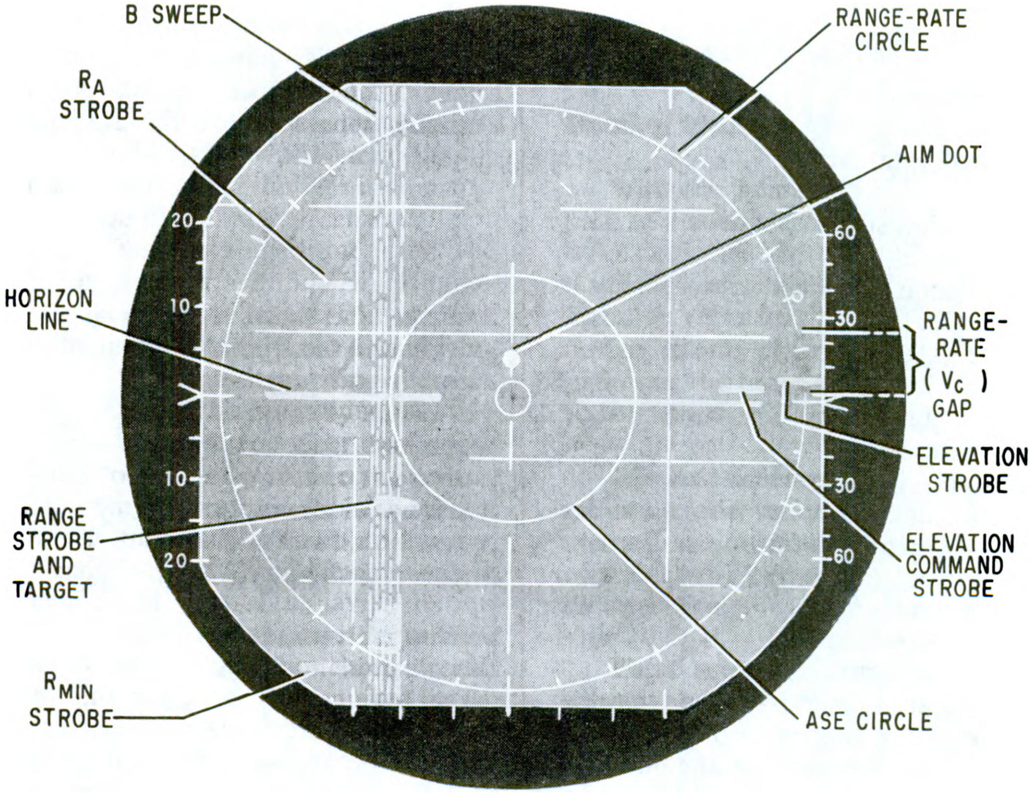


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Figure 4-31.—Composite A-B gun display, track presentation.

2. Track operation only
    - Range-rate circle and gap
    - Allowable steering error (ASE) circle
    - Aim dot
    - Breakaway-X
    - Elevation command strobe
    - Elevation strobe
3. Data link operation
    - Data link circle
    - Data link dot
    - Elevation strobe
    - Elevation command strobe
    - Elevation strobe
4. SEAM operation
    - SEAM circle
    - SEAM dot
    - Range rate circle
    - Elevation strobe
    - Elevation command strobe

Figure 4-29 shows the A-gun display in the search presentation and figure 4-31 shows the composite A-B gun display. The symbols shown on the illustrations and not listed above are generated by the circuits of the B-gun channel. These symbols include the B-sweep, the target video and range strobe, the acquisition symbol, and the R_a and R_{min} strobes.

The A-gun symbols are all produced in the same manner. Appropriate signal voltages are applied to the horizontal and vertical deflection plates of the storage tube to form the symbol. At the same time, discreet intensity pulses, adapted in amplitude and duration to the individual symbols, are applied to the intensity grid of the storage tube to illuminate the symbols. The various symbols are generated simultaneously and, by means of a time-sharing system, are displayed simultaneously by a single channel. The high persistence of the storage tube aids in the presentation by preventing the symbols from fading during the off periods.

During all operating conditions of the radar, the horizon line appears as a straight line across the display screen, with its center third blanked out. The purpose of the horizon line is to provide the pilot with a constant indication of the aircraft attitude with respect to the ground. The horizon line, therefore, duplicates most of the information presented by the artificial horizon of the aircraft attitude indicator mounted in the pilot's flight control panel. This duplication is necessary because it permits the pilot to fly the aircraft during an intercept operation without being distracted form the radar display. When the aircraft rolls, the horizon line tilts according to the roll angle. Since a climb or dive angle is also measured with respect to the ground, the angle is proportional to the displacement of the horizon line from the center of the screen in a direction perpendicular to itself (and to the ground). During level flight, the line is horizontal and in the center of the display screen.

The horizon line is generated by applying two sine waves, either in phase or 180° out of phase, to the vertical and horizontal deflection plates. These signals, referred to as the vertical and horizontal roll signals respectively, determine the length and slope of the horizon line. Two additional sine waves, whose amplitudes are proportional to the pitch (climb or dive) angle of the aircraft, are applied to demodulator circuits in the indicator control unit. The demodulated and filtered outputs of these circuits are added to the roll deflection signals as dc levels, which determine the pitch displacement of the horizon line.

The elevation strobe consists of a short horizontal line (approximately 1/4 inch long) displayed on the right side of the screen during all operating conditions of the radar. Its vertical position indicates the antenna elevation angle with respect to the horizon, which may be read (up to ±60°) on the elevation (EL) scale etched on the right side of the screen face.

The horizontal position of the elevation strobe is determined by the upper amplitude level of a 400-Hz square wave applied to the horizontal deflection plates of the storage tube. A small 20-KHz sine wave is superimposed upon the square wave to make the symbol appear as a short line rather than as a dot. A properly timed intensity pulse causes the elevation strobe to appear on the display during all operating conditions.

The vertical position of the elevation strobe is determined by a 400-Hz sine wave input, whose amplitude is proportional to the elevation angle of the radar antenna. This signal, after being demodulated and filtered, is applied to the vertical deflection plates during the time interval that the half of the square wave representing the elevation strobe horizontal position is applied to the horizontal deflection plates.

When a target has been acquired and the radar begins automatic range tracking, the fixed 3 1/4-inch diameter range-rate (Vc) circle is presented on the display with a 1/4-inch range-rate gap in its perimeter. The circle acts as a carrier for the gap, and the instantaneous position of the gap indicates the relative speed (range rate) between the interceptor and the target. When a constant range is being maintained between interceptor and target, the range rate is zero and the gap appears at the 12 o'clock position (called the zero position). Clockwise displacement of the gap indicates that the range between interceptor and target is decreasing at a speed proportional to the angular position at which the gap comes to rest. This speed is referred to as the closing range rate. Similarly, counterclockwise displacement of the gap indicates that the range between interceptor and target is increasing at a speed (called the opening range rate) proportional to the final angular position of the gap. A fairly accurate indication of the range rate is provided by means of the graduations etched around the periphery of the indicator face.

In developing the range circle, a 940-Hz oscillator circuit in the indicator control produces a sine wave which is fed to a phase-shift network. The output of the phase-shift network consists of two 940-Hz sine waves 90° out of phase with each other. These two signals are applied to the horizontal and vertical deflection plates, respectively, thereby producing a circle on the screen. The range-rate is generated by applying the oscillator output to another phase-shift network. This network produces a single 940-Hz sine wave variable from +40° to −50°, with respect to its input. The phase of this signal is adjusted to set the range-rate gap at 12 o'clock when the range rate is zero. This signal is then processed in the circuits of the indicator control and combined with a reference voltage (called the dc range-rate voltage) from the computer in the CW radar system. Then, the resulting pulse output is employed as a blanking pulse to the intensity grids of the indicators. This produces the required gap at a position on the range-rate circle determined by the amplitude of the dc range-rate voltage.

While in the track operation, the radar display includes a circle (of varying diameter) that represents the allowable steering error within which successful missile launch can be made. If lock-on is achieved at the maximum limit of the air intercept (AI) ranges (50 miles), only a very small steering error can be tolerated, and the ASE circle may close to its minimum size of 0.4 inch in diameter. The size of the circle increases as the range decreases, until it reaches its maximum size at the moment that the IN RANGE (IN RNG) on the pilot's indicator lamp on the indicator bezel lights up. The lighting of the IN RNG lamp indicates that the target range is now within both the maximum aerodynamic limits and the maximum seeker limits of the selected missile. As the range decreases from this point, the size of the circle begins to decrease too. This decrease in size accounts for the decreasing flying time during which the missile can correct for a steering error. The ASE circle reaches its minimum diameter as the target range reaches R_{min}. Beyond the R_{min} range, the entire track presentation disappears and the breakaway-X symbol is presented.

For systems with SEAM, a SEAM circle is displayed during SEAM operation and the ASE circle is extinguished if the radar set is in track. The break-X relay is also disabled in SEAM and no break-X symbol is available.

The ASE circle is generated in the same manner as the range-rate circle; however, no blanking pulse is provided to generate a gap, and the 940-Hz deflection signals vary in amplitude to produce a circle of varying diameter. The amplitude variation of the deflection voltages during normal track operation is produced by means of a varying dc bias voltage obtained from the computer in the CW radar system.

The actual steering error, or deviation of the aircraft from its required course, is indicated in the display screen by the position of a moving dot called the steering error dot or aim dot. For a perfect course, the dot would be centered on the display. However, since some deviation can be tolerated, the pilot is only required to guide his aircraft so the aim dot stays within the limits of the ASE circle.

The R_{min} strobe included in the track presentation indicates the minimum range at which a missile may be fired. If the target symbol drops below the R_{min} strobe at any time during track operation, the IN RANGE lamp goes out. The BREAK lamp lights, the track presentation disappears from the screen, and the the breakaway-X appears as an indication to the pilot that he is too close to the target and must alter the course. The breakaway symbol appears in the center of the screen as a script letter X approximately 1 inch high.

The X-symbol is formed by producing a 2:1 Lissajous figure on the screen and blanking out the two ends of the pattern. A 400-Hz sine wave is applied to the vertical deflection plates and a 200-Hz sine wave to the horizontal plates, thereby causing the electron beam to the storage tube to complete two vertical sweeps for every single horizontal sweep.

The symbol-generating circuits described in the preceding paragraphs operate continuously and simultaneously. Obviously, if the various symbol signals were to be applied to the deflection plates at the same time, a completely unintelligible display would result. Thus, time-sharing is used in the A-gun channel. With the aid of the persistence characteristics of the storage tube, the simultaneous display signals are passed through diode signal switches that are gated in sequence by the outputs of a time-sharing gate generator. From the outputs of these diode switches, the signals are applied to the deflection plates one at a time and in the sequence desired. A complete time-sharing cycle lasts 20 milliseconds, and since the shortest persistence in the storage tube in the order of 100 milliseconds, the display screen can present the illusion of a continuously generated display.

Each of the symbol signals applied to the deflection plates is accompanied by appropriate intensity pulses applied to the storage tube intensity grids. When no deflection signals are being applied, the display screen remains blanked out. The intensity pulses are adapted, in amplitude and duration, to the size and writing speed of the individual symbols; this allows a composite display of uniform brightness to be presented on the screen. Additionally, several of the symbols have certain peculiar requirements that are most easily served by means of intensity control. Some of these symbols are the range-rate circle, in which the position of the gap is determined by a properly timed blanking pulse; the breakaway-X, which has an intensity pulse timed to blank out the ends of the symbol; and the elevation strobe, aim dot, data link dot, and SEAM dot which employ intensity control to prevent the appearance of undesired symbols on the screen.

GENERAL DESCRIPTION OF B-GUN DISPLAY.—The B-gun channel generates the B-sweep, the acquisition symbol, the R_a and R_{min} strobes, the target video, the range strobe, and the bombing range strobe. These symbols are shown in the composite A-gun and B-gun displays of figures 4-29, 4-30, and 4-31. The B-sweep and target video appear in all conditions of the radar in which the transmitter is operating. The acquisition symbol appears in all conditions of the system except track. After lock-on has been achieved, the acquisition symbol is replaced by the R_a and R_{min} strobes.

Unlike the signals for the A-gun symbols, which are completely independent of one another, the signals generated in the B-gun channel are interdependent and exercise definite control over each other. The target video and the range strobe are displayed as intensified spots on the B-sweep (fig. 4-30). When the lock-on switch on the radar control stick is pressed to the half-action position, the B-sweep slews to the azimuth position of the acquisition symbol. After lock-on, the R_a and R_{min} strobes maintain a constant azimuth position with respect to the B-sweep. In addition to this feature of interdependence, the B-gun presentation is synchronized with the pulse repetition frequency (PRF) of the transmitted radar pulses (radar trigger), whereas the A-gun symbols require no synchronization with the action of other portions of the radar set.

The B-sweep appears as a vertical line moving across the width of the radar screen in coordination with the azimuth movement of the antenna. The sweep line is horizontally centered on the screen when the antenna is pointed straight ahead. A maximum sweep displacement to the left or right from center represents an antenna swing of 60° when the system is in wide scan. The overall height of the B-sweep line, although constant, may represent a total range of 10, 25, 50, 100, or 200 miles, depending upon the setting of the RANGE switch on the radar set control panel. For each such setting, the range at any intermediate point on the B-sweep is proportional to the height of that point from the base of the display.

Sometimes it is necessary to magnify certain portions of the range sweep for a better view of suspected targets. This can be done by selecting a short length of the sweep that represents the range sector of interest and then expanding that sector to cover the entire height of the display. When the DISPLAY switch on the radar set control is set at the EXP position, the start of the B-sweep is delayed from the radar trigger by an interval corresponding to the distance between the interceptor and the range at which the expanded sweep starts.

The B-azimuth signal (fig. 4-30 and fig. 4-31), a 400-Hz voltage modulated by a triangular envelope that corresponds to the horizontal component of the antenna motion, is demodulated and filtered. The resulting signal is applied to the B-gun horizontal deflection plates of the storage tube. This sweep voltage causes the B-sweep to move across the screen, thus indicating the azimuth angle of the antenna scan. During acquisition and track operation, a 50- to 70-Hz voltage is superimposed upon the horizontal deflection signal. This voltage produces a dither in the B-sweep and causes it to appear wider to ensure its visibility, as shown in figures 4-30 and 4-31. This voltage is the output of the azimuth spin generator, and its frequency corresponds to the nutation frequency of the antenna feedhorn.

The acquisition symbol appears on the screen of the storage tube as two short vertical lines approximately 1/4 inch apart. The position of the symbol in range and azimuth is controlled manually by the RIO as the radar control stick is moved to the desired position. During search operation, the antenna scans automatically, and its position is not affected by the movement of the radar control stick. Nevertheless, the RIO can use the control stick to bracket a desired target with the acquisition symbol. Also, when the lock-on switch on the radar control stick is pressed to the half-action position, the antenna slews to the azimuth position of the acquisition symbol and operates under manual control as shown in figure 4-30. The position of the acquisition symbol is adjusted so that the range strobe, which appears on the B-sweep during acquisition and track, is directly over the desired target. If the lock-on switch is next pressed to the full-action position, the radar locks on the target and the antenna begins to track automatically. Then the acquisition symbol disappears, and the track presentation shown on figure 4-31 is displayed.

The R_a and R_{min} strobes are two short horizontal lines appearing slightly to the left of the B-sweep during track operation. The R_a strobe indicates the maximum target range for firing a missile in a particular tactical situation, taking into account only the maximum aerodynamic range of the missile. This range, which is calculated in the range computer of the CW radar system, is dependent upon such factors as altitude, true air speed, and closing velocity between interceptor and target. When the range between interceptor and target decreases to the point where it is within the limits of both the R_a range and the maximum seeker range of the missile, the IN RNG lamp on the indicator bezel lights. The R_{min} strobe indicates the minimum range at which a missile can be fired and still be capable of receiving CW guidance. As the target falls below the R_{min} range, the track presentation disappears from the display screen and the breakaway-X appears as an indication to the pilot to alter his course in order to avoid a collision. If the missile is fired at the R_{min} range, the pilot can still alter his course without depriving the missile of its required guidance, provided the angle at which he breaks away does not exceed the gimbal limits of the antenna.

The R_a and R_{min} strobe signals from the computer are passed through two switch gates that are activated alternately so that each strobe is written on the display screen on alternate radar triggers. The horizontal deflection signal consists of the B-sweep azimuth signal, slightly attenuated, with a 20-KHz signal superimposed to provide length to the strobes.

The target video and the range strobe are both displayed on the indicator screen as intensified spots on the B-sweep. The target video display includes actual targets, details of terrain, and clutter due to jamming interference or weather. During all operating conditions except mapping, the range gate pulse from the synchronizer is applied to the input of the RIO B-gun horizontal deflection amplifier. This short pulse (0.4 microsecond) causes a momentary deflection of the B-sweep (fig. 4-29). In the acquisition and track conditions, the B-sweep is intensified at the point of this deflection, and this brightened spot, combined with the dither of the B-sweep, appears as the range strobe.

During search and acquisition, the range strobe is generated in the range tracking system as a function of the radar control stick position. During track, the range strobe becomes a function of range computed in the range tracking system. Although generated continuously, the range strobe signal is permitted to pass to the indicators only during conditions of half action, full action, automatic track, or manual track.

The bombing range strobe (fig. 4-29) provides a range reference in the bomb mode of operation and is used by the pilot and the RIO to determine target ranges. The target position is compared to the known bombing range strobe position.

Of the B-gun symbols which are generated by means of voltages applied to the deflection plates, only two are displayed at any given time. During search and acquisition, the displayed symbols are the B-sweep and the acquisition symbol. During track, the B-sweep and the R_a and R_{min} strobes are displayed. Time-sharing employed in the generation of these symbols involves two active periods. One period is for the video display; and one period is for the acquisition symbol (or R_a R_{min} strobes) display, followed by dead time that lasts until the next radar trigger. During the video display period, the B-sweep signals are applied to the deflection plates. During the symbol displayed period, either the acquisition symbol signals or the R_a and R_{min} strobe signals are applied to the deflection plates, depending upon the operating condition. The time-sharing action is accomplished by means of transistor switches (one horizontal and one vertical) being activated during each of the above-mentioned switching periods.

To generate a visible display on the screen, an intensity signal must be applied to the control grids of the storage tubes at the same time the vertical and horizontal voltages are being applied to the deflection plates. The amplitude and duration of each of these intensity pulses vary according to the size and shape of the individual symbol, and the pulses must be accurately timed to blank out any undesired portions of the symbols.

CW RADAR SET GROUP

The CW radar set group, used with the previously discussed AI type of radar missile control system, provides a modulated CW-RF signal. When transmitted by the antenna of the AI radar, this signal is used to illuminate an airborne target. When reflected from the target, the signal is used with the modulated CW-RF signal received directly. These signals are used by the CW radar target seeker in an air-to-air type of missile (semiactive homing) to guide the missile toward interception of the target aircraft. It also provides signals for prelaunch tuning and control of the missile and additional signals that are used by the AI radar to provide the pilot with adequate information to fully use the capabilities of the aircraft/missile combination.

PRINCIPLES OF OPERATION

The CW radar set group uses three frequencies. The primary, or magnetron frequency, is normally called the **A** frequency. This is the fundamental CW radio-frequency. However, identification of the signal requires coding of the **A** frequency by frequency modulating it with a frequency referred to as the **B** frequency. The **A** frequency is also frequency modulated by another frequency, for range information to the missile, by a frequency referred to as the **C** frequency. The frequency **B** coding signal is also amplitude modulated at the frequency **C** rate and is used for range reference in the missile. Thus, the emission from the AI antenna is actually a CW signal that has been frequency modulated by multiple signals.

The power output delivered to the AI antenna from the CW radar determines the missile's normal control range. This range varies, depending upon the condition of the equipment, atmospheric conditions, and aircraft altitude at time of launch.

The normal type of AI radar, when used with the CW system, must be modified with a duplexing arrangement. This arrangement makes the AI radar antenna capable of handling both CW and pulsed signals simultaneously.

The CW radar set group accepts target range information from the AI radar and computes the target's closing velocity. It is used in conjunction with the launching aircraft's true air speed and altitude data to provide fire control information to the guided missile launching set. In addition, range data from the AI radar is used by the CW radar set group to produce a simulated Doppler signal that is within the region of the Doppler signal to be received by the missile's target-seeker group. The simulated Doppler signal is applied to the missile's speed gate circuits, causing it to lock in the anticipated Doppler frequency region.

Prior to launch (out of range), the CW radar set group transmits pseudo and rear signals to the missile. A portion of the transmitted energy is picked off and fed to the pseudo and rear signal circuits. The psuedo signal is produced by a crystal modulating tee operating as a single sideband that mixes two signal inputs from the computer-modulator with the transmitted energy. Then the upper sideband output is coupled to the port and starboard pseudo antenna horns and picked up by the missile. The rear signal is distributed to the rear antenna horns through a magic-T and picked up by the missile's rear receiver. These front and rear signals are compared, and they effect the tuning of the missile's local oscillator. When the pilot closes the master armament switch in the cockpit, the pseudo signal is turned off, and the simulated Doppler signal is applied to the missile's speed gate.

The AI radar antenna angle and rates are used by the CW radar set group to provide head aim and attitude control voltages for the missile plus lead angle steering signals for use by the AI radar attack display. Lead angle error signals are used by the lead angle interlock circuit in conjunction with the in-range interlock circuits to prevent firing of the missile when the range is above maximum or below minimum, or lead angle is excessive.

UNIT FUNCTIONS

The CW radar set group is composed of a computer-modulator, power supply, radar transmitter and cooling system, and a flight data computer. The basic functions of the CW radar set group and the essential flow of intelligence between the major components of the missile control system in its missile function are shown in figure 4-32. The functions are simplified to show the type of information exchanged within the missile control system and do not represent the actual circuit connections. You should refer to figure 4-32 while reading about the functions of the CW radar units.

Computer-Modulator (Unit 1)

The computer assembly (lower half of the computer-modulator, unit 1) performs the following functions:

- It receives and processes target range signals from the AI radar and true airspeed and altitude pressure signals from the flight data computer (unit 4). It furnishes a range interlock to the launching set indicating when a specific target is within range of the missile. These signals are also processed to provide firing range to go, and maximum range information for use by the AI radar.

- It receives target range and azimuth and elevation rates from the antenna. It furnishes the missile head-aim and attitude control (English-bias) voltages and lead angle steering information (aim-dot) to the AI radar display. The head aim output signal is a summation of antenna rate and position, plus range applied to the missile's head control circuits to slave the missile's front antenna with the AI radar's antenna at launch. The English-bias output is also a summation of antenna rate and position, plus range applied to the missile's flight control circuits to actuate control surfaces in establishing the proper missile collision attitude. The aim-dot output is fed to the AI radar indicator as the summation of antenna rate and position, plus range, thus providing a lead pursuit course steering aid in the form of a dot on the attack display.

- It receives and processes altitude pressure data from the flight data computer for use by the missile's autopilot gain control circuit. Thus, with a given angular error, the magnitude of the steering signals applied to the control surface servosystem is a function of the altitude of the missile at launching.

- It processes the target signal range to provide a simulated Doppler signal that corresponds to the expected signal of the specific target. The simulated Doppler output signal is fed to the missile and locks the missile's speed gate in the region of the target Doppler.

The modulator assembly of the computer-modulator performs the following functions:

- It supplies the voltage used by a ferrite isomodulator to frequency modulate the CW magnetron/klystron at a frequency **C** rate to provide range information to the missile.

- It provides the voltage used by a ferrite isomodulator to frequency modulate the CW magnetron/klystron at a frequency **B** rate to provide coding that is used to identify the illuminating source to the missile.

- Its amplitude modulates the frequency **B** coding signal at a frequency **C** rate to provide range reference for the CW target seeker of the missile.

- It provides a frequency-modulated voltage (frequency **C** deviation) to be used to provide artificial target closing velocity and range information (pseudo signal) to effect the tuning of the missile's local oscillators and to indicate proper missile target seeker operation prior to launch.

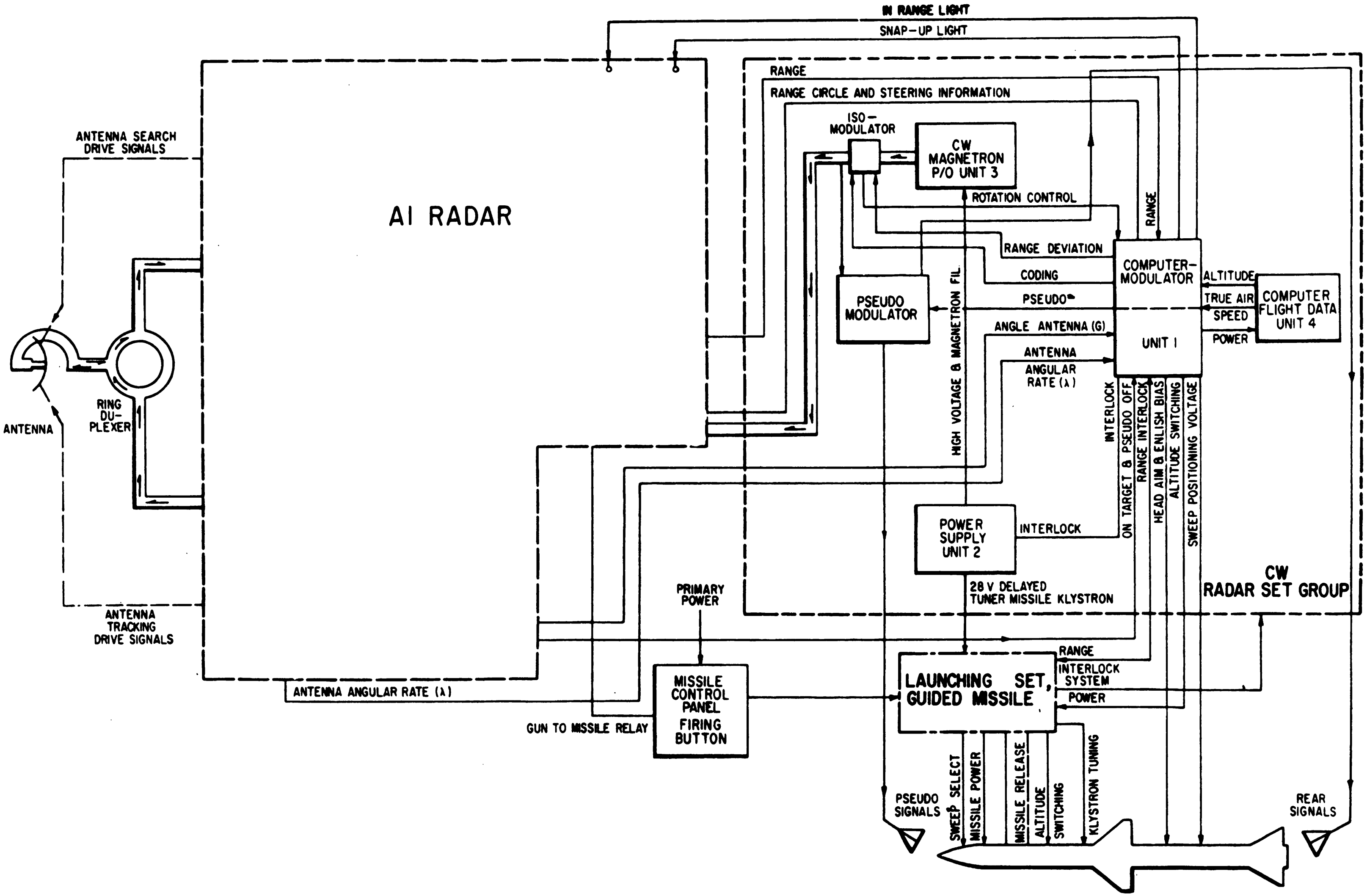

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Figure 4-32.—Typical airborne missile control system, functional block diagram.

- It accepts and processes information at the ranging frequency from the isomodulator (P/O Unit 3) to effect bias rotation control of the isomodulator. An interlock is included for protection of the CW magnetron/klystron in the event of failure of the bias rotation voltage supply.

Power Supply (Unit 2)

The power supply provides the filament and high voltage source for the magnetron/klystron. It contains a cam-operated time delay circuit for proper operation of the system. This time delay circuit controls the application of the filament voltage to the magnetron/klystron and 28-V dc (delayed) to the klystron tuners located in the missile pylons.

The unit is mounted in a pressurized shock-mounted case to allow operation at high altitudes. Cooling is accomplished by means of ram air forced through a plenum chamber where grooves in a cold plate deck aid in extracting heat. Two ports on the case provide air intake and exhaust for the plenum chamber.

Radar Transmitter (Unit 3)

The radar transmitter consists of a magnetron/klystron assembly (newer systems use a multicavity klystron vice a magnetron), three CW isolators, two additional waveguide couplers, a filter-T assembly, a pseudo modulating T, two magic-Ts, two pseudo signal horns, two rear signal horns, and the magnetron cooling system. The radar transmitter performs the following functions:

- It generates the CW-RF carrier signal.

- Its frequency modulates the CW-RF carrier at a frequency **B** which is the coding signal used to identify the illuminating source to the missile.

- Its frequency modulates the CW-RF output signal with a frequency **C** signal for use by the CW radar target seeker of a missile for range reference.

- It provides suitable coupling, filtering, and isolation for the CW and pulse RF signals.

- Its single sideband modulates an RF carrier signal with a pseudo Doppler frequency.

- It distributes and radiates a portion of the FM-CW carrier signal by means of the two rear signal horns.

- It distributes and radiates the modulated pseudo signal by means of the two pseudo signal horns.

The magnetron assembly is the RF power source of the radar transmitter. It consists of a CW magnetron/klystron, an isomodulator with a crystal detector, and associated plumbing.

The microwave power source for CW illumination is a high-power type of magnetron/klystron operating at **A** frequency. If a target were illuminated with pure CW energy alone, the reflected energy would provide only target speed, target direction, and warhead detonation information to the missile during flight. In order to provide other necessary information to the missile, the transmitted energy is frequency modulated.

Frequency modulation is accomplished through the use of an isomodulator located at the output of the magnetron/klystron. The isomodulator is a ferrite device capable of rotating the plane of polarization of its microwave input. Two coils in this device receive **B** frequency and **C** frequency modulating signals from the computer-modulator. The input and output connecting waveguide portions of the isomodulator differ in polarization and, in the absence of modulation signals in the two coils, all of the CW energy is allowed to pass through. When the rotating plane of polarization is caused to depart slightly by the modulating signals, the output polarization is no longer correct for complete transmission. Consequently, a controlled mismatch is created at the output flange of the isomodulator. A portion of the microwave energy is reflected back through the isomodulator input guide to the magnetron/klystron, and the isomodulator location is such that this reflected energy pulls the magnetron/klystron at the two modulation frequencies.

The **B** frequency signal that frequency modulated the **A** frequency signal is used for coding. This coding frequency is detected in the missile at the output of the rear IF amplifier and is used to identify the missile with the illuminator of its own launching aircraft.

The **B** frequency is amplitude modulated at **C** frequency providing range reference to the missile.

A **C** frequency signal frequency modulates the **A** frequency signal to provide range information to the missile. The **C** frequency FM is reflected from the target and is received by the missile's front antenna. The **C** frequency signal is extracted and compared with the range reference to detect a phase difference proportional to target range. This intelligence is used by the range arming circuit of the missile.

The CW injection plumbing, consisting of the waveguide and associated detail parts required to inject high-power microwave energy into the antenna of the AI pulse radar, is located in the nose section of the aircraft. The injection plumbing performs the following functions:

- It directs microwave energy from the CW magnetron/klystron to the antenna of the AI radar.

- It prevents CW energy from entering the receiver of the pulse radar and, in turn, prevents pulse energy from affecting the CW magnetron/klystron.

- It prevents antenna search and scan variations from pulling the CW magnetron/klystron away from its nominal frequency.

- It provides couplers for picking off energy for the rear and pseudo signal horns.

The CW magnetron/klystron is isolated from target reflections which return in the same plane of polarization as the energy being transmitted. If allowed to enter the output arm of the waveguide, the reflected energy would cause the magnetron/klystron to be pulled off frequency. Therefore, three isolators are used in the output arm of the waveguide to provide the necessary isolation. The isolator is a ferrite device that is also capable of rotating the plane of polarization of microwave energy passing through it. The ferrite in the isolator is nonreciprocal; that is, the plane of polarization of energy passing back through the ferrite is rotated in the same direction as the energy being transmitted.

The output waveguide of each isolator is rotated with respect to its input waveguide to allow complete transmission of the energy entering the isolator. Positioning the input guide of each isolator in the series is automatically governed by the plane of polarization of the energy leaving the preceding isolator (or isomodulator in the case of the isolator in the series). Consequently, the vertically polarized energy that enters the isomodulator is rotated through the action of the

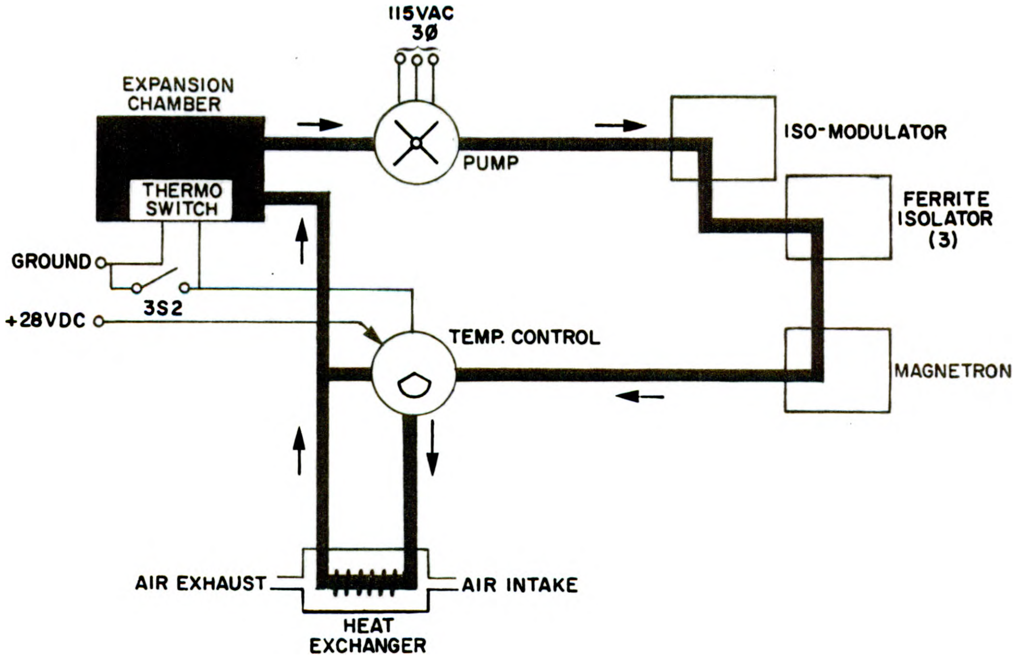

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Figure 4-33.—Magnetron cooling system, functional block diagram.

isomodulator and the three isolators and is transmitted in the vertical plane of polarization.

Energy reflected from the target is in the correct plane of polarization to enter the transmission line. However, as the energy passes through the isolator, the ferrite rotates it, which causes it to be at right angles to the isolator input guide. In this way, the unwanted energy rejected through the nonreciprocal action of the ferrite in each of the three isolators is dissipated in the side arm. A side arm load is located at the input guide in the correct plane to dissipate the unwanted energy.

The magnetron/klystron cooling system is a closed system that dissipates excessive heat from the magnetron and associated ferrite parts. Figure 4-33 is a functional block diagram of the cooling system. It consists of an expansion chamber, pump, temperature control valve, and a heat exchanger.

When system power is applied, the cooling system receives input power to the pump and to a thermoswitch in the expansion chamber. The pump operates continuously, circulating the coolant. The temperature control valve is a three-way valve that controls the return of the coolant to the expansion chamber. If the coolant has been heated to a temperature of 60°F by the magnetron/klystron, the thermoswitch closes, applying 28-V dc to the control valve. This voltage energizes a solenoid within the valve which, in turn, opens the valve outlet to the heat exchanger. The heated coolant passes through the heat exchanger, where it is cooled, and returns to the expansion chamber. The heat exchanger is supplied with ram air that absorbs the dissipated heat of the coolant.

When the coolant falls below 60°F the thermoswitch opens, causing the control valve solenoid to de-energize. The valve will then direct the coolant back to the expansion chamber, bypassing the heat exchanger.

REFERENCE

Aviation Fire Control Technician 1 & C, NAVEDTRA 10390-C, chapter 8.

CHAPTER 5

CONTROLLING ELECTRICAL NOISE

The electrical noise generated in a radio or radar receiver is often confused with electrical noise generated external to the receiver and coupled into the receiver. The internally generated noise is the result of circuit deficiencies in the receiver itself and can be eliminated by replacing defective components in the receiver or by replacing the entire receiver. Electrical noise produced external to the receiver enters the receiver by various means. The noise causes interference in and poor reception by the receiver.

In addition to the poor performance of a receiver, the external noise leaking into a computer system may cause the system to be completely inoperative. The noise combines with timing pulses in the computer, making the computer useless. Other types of interference can cause a computer-controlled attack display to jitter and make its accuracy decrease or become completely inaccurate.

As a first class or chief petty officer, you should be aware of these indications because the people who work for you will come to you for help. Many of these problems are rare, and they are only seen by those with many years of experience. The objective of this chapter is to help you to recognize various types of electrical noise and the effects of the noise upon certain types of equipment. This chapter also provides information on keeping electrical noise interference as low as possible in the electronic equipment aboard naval aircraft. When you finish reading this chapter, you will be able to recognize the following:

- Types and effects of radio noise and identify the source as natural or man-made interference

- Various sources of electrical noise and the characteristics of each

- Various types of interference caused by coupling and how to reduce them

- Various methods and components used to reduce radio interference caused by electrical noise

- Purpose, types, and techniques of bonding

TYPES AND EFFECTS OF RECEIVER NOISE INTERFERENCE

The types of electrical noise interference that enter aircraft receivers are broadly categorized as natural interference and man-made interference.

NATURAL INTERFERENCE

Radio interference caused by natural electrical noise is separated into three types: atmospheric static, precipitation static, and cosmic noise. Each type is discussed below.

Atmospheric Static

Atmospheric static is a result of the electrical breakdown between masses (clouds) of oppositely charged particles in the atmosphere. An extremely large electrical breakdown between two clouds or between clouds and the ground is called lightning. Atmospheric static is completely random in nature, both as to rate of recurrence and as to intensity of individual discharges. Atmospheric static produces irregular popping and crackling in audio outputs and "grass" on visual output devices. Its effects range from minor annoyance to complete loss of receiver usefulness. Atmospheric interference is seldom of a crippling intensity at frequencies above 2 MHz. However, it can be annoying up to 30 MHz. Above this frequency, the noise intensity decreases to a very low level. At frequencies below 2 MHz, natural static is the principal limiting factor on usable receiver sensitivity.

The intensity of atmospheric static varies with location, season, weather, time of day, and the frequency to which the receiver is tuned. It is most intense at the lower latitudes, during the summer season, during weather squalls, and at the lower radio frequencies. Many schemes have been devised to minimize the effect of atmospheric static. However, the best technique is to avoid those frequencies associated with intense static, if possible.

Precipitation Static

Precipitation static is a type of interference that occurs during dust, snow, or rain storms. The principal cause of precipitation static is the corona discharge of high-voltage charges from various points on the airframe. These charges may reach several hundred thousand volts before discharge occurs. The charge can be built up in two ways. First, an electrostatic field existing between two oppositely charged thunderclouds induces bipolar charges on the surfaces of the aircraft as it passes through the charged clouds. Second, a high unipolar charge on the entire airframe occurs from frictional charging by collision of atmospheric particles (low altitudes) or fine ice particles (high altitudes) with the aircraft's surface. The effects of corona discharge vary with temperature. The effects are greater with altitude and increase with an increase in airspeed. Doubling airspeed increases the effect by a factor of about 8; tripling airspeed increases the effect by a factor of about 27.

The effect of precipitation static is a loud hissing or frying noise in the audio output of a communication receiver and a corresponding "grass" indication on a visual output device, such as a radar receiver. The radio frequency range affected by precipitation static is nearly the same as for atmospheric static. When present, precipitation interference is severe and often totally disables all receivers tuned to the low- and medium-frequency bands.

Cosmic Noise

Cosmic noise is usually heard in the UHF band and above; however, it is occasionally heard at frequencies as low as 10 MHz. Cosmic noise is caused by the radiation of stars. Although its effect is generally unnoticed, at peaks of cosmic activity cosmic-noise interference could conceivably be a limiting factor in the sensitivity of navigational and height-finder radar receivers.

MAN-MADE INTERFERENCE

Man-made interference is generally categorized according to the spectrum of its influence, such as broadband and narrow band. Each type of man-made interference is discussed below.

Broadband Interference

Broadband interference is generated when the current flowing in a circuit is interrupted or varies at a rate which departs radically from a sinusoidal rate. A current whose waveform is a sine wave is capable of interfering at only a single frequency. Any other waveform contains harmonics of the basic frequency. The steeper the rise or fall of current, the higher the upper harmonic frequency will be. A perfect rectangular pulse contains an infinite number of odd harmonics of the frequency represented by its pulse recurrence rate. Typical types of electrical disturbances that generate broadband interference are electrical impulses, electrical pulses, and random noise signals.

For the purposes of this discussion, impulse is the term used to describe an electrical disturbance, such as a switching transient that is an incidental product of the operation of an electrical or electronic device. The impulse recurrence rate may or may not be regular. Pulse is the term used to describe an intentional, timed, momentary flow of energy produced by an electronic device. The pulse recurrence rate is usually regular.

Switching transients or impulses result from the make or break of an electrical current. The pulses are extremely sharp pulses. The duration and peak value of these pulses depend upon the amount of current and the characteristics of the circuit being opened or closed. The effects are sharp clicks in the audio output of a receiver and sharp spikes on an oscilloscope trace. The isolated occasional occurrence of a switching transient has little or no significance. However, when repeated often enough and with sufficient regularity, switching transients are capable of creating intolerable interference to audio and video circuits, thus degrading receiver performance. Typical sources of sustained switching transients are ignition timing systems, commutators of dc motors and generators, and pulsed navigational lighting.

Pulse interference is normally generated by pulsed electronic equipment. This type of interference is characterized by a popping or buzzing in the audio output device and by noise spikes on an oscilloscope. The interference level depends upon the pulse severity, repetition frequency, and regularity of occurrence. Pulse interference can trigger beacons and IFF equipment and cause false target indications on radar screens. In certain types of navigational beacons, these pulses cause complete loss of reliability.

Random noise consists of impulses that are of irregular shape, amplitude, duration, and recurrence rate. Normally, the source of the random noise is a variable contact between brush and commutator bar or slip ring, or an imperfect contact or poor isolation between two surfaces.

Narrow-Band Interference

Narrow-band interference is almost always caused by oscillators or power amplifiers in receivers and transmitters. In a receiver, the cause is usually a poorly shielded local oscillator stage. In a transmitter, several of the stages could be at fault. The interference could be at the transmitter operating frequency, a harmonic of its operating frequency, or at some spurious frequency. A multichannel transmitter that uses crystal-bank frequency synthesizing circuits can produce interference at any of the frequencies present in the synthesizer. Narrow-band interference in a receiver can range in severity from an annoying heterodyne whistle in the audio output to the complete blocking of received signals. Narrow-band interference affects single frequencies or spots of frequencies in the tuning range of the affected receiver.

SOURCES OF ELECTRICAL NOISE

Any circuit or device that carries a varying electrical current is a potential source of receiver interference. The value of the interference voltage depends upon the amount of voltage change. The frequency coverage depends upon the abruptness of the change. The principal sources of man-made interference in aircraft include rotating electrical machines, switching devices, pulsed electronic equipment, propeller systems, receiver oscillators, nonlinear elements, and ac power lines. Each of these sources of noise is discussed below.

ROTATING ELECTRICAL MACHINES

Rotating electrical machines are a major source of receiver interference because of the large number of electric motors used in the aircraft. Rotating electrical machines used in aircraft may be divided into three general classes: dc motors, ac motors and generators, and inverters.

Dc Motors

Dc motors are used in great numbers in modern aircraft as flight control actuators, armament actuators, and flight accessories. Many electronic equipments on the aircraft include one or more dc motors for driving cycling mechanisms, compressor pumps, air circulators, and antenna mechanisms. Each of these motors can generate voltages capable of causing radio interference over a wide band of frequencies. Types of interfering voltages generated by dc motors are listed below.

- Switching transients generated as the brush moves from one commutator bar to another (commutation interference)

- Random transients produced by varying contact between the brush and the commutator (sliding contact interference)

- Audio-frequency hum (commutator ripple)

- Radio frequency and static charges built up on the shaft and the rotor assembly

Dc motors used in aircraft systems are of three general types: the series-wound motor, the shunt-wound motor, and the permanent-magnet (PM) motor. The field windings of both series- and shunt-wound motors afford some filter action against transient voltages generated by the brushes. The PM motor's lack of such inherent filtering makes it a very common source of interference. The size of a dc motor has little bearing upon its interference-generating characteristics. The smallest motor aboard the aircraft can be the worst offender.

Ac Generators and Motors

The output of an ideal alternating-current generator is a pure sine wave. A pure sine-wave voltage is incapable of producing interference except at its basic frequency. However, a pure waveform is difficult to produce, particularly in a small ac generator. Nearly all types of ac generators used in naval aircraft are potential sources of interference at frequencies other than the output power frequency. Interference voltages are produced by the following sources:

- Harmonics of the power frequency. Generally, the harmonics are caused by a poor waveform.

- Commutation interference. This condition originates in a series-wound motor.

- Sliding-contact interference. This condition originates in an alternator and in a series-wound motor.

Generally, an ac motor without brushes does not create interference.

Inverters

An inverter is a dc motor with armature taps brought out to slip rings to supply an ac voltage. The ac output contains some of the interference voltages generated at the dc end as well as the brush interference at the ac end of the inverter.

SWITCHING DEVICES

A switching device makes abrupt changes in electrical circuits. Such changes are accompanied by transients capable of interfering with the operation of radio and other types of electronic receivers. The simple manual switch (occasionally operated) is of little consequence as a source of interference. Examples of switching devices (frequently operated) capable of causing appreciable or serious interference are the relay and the thyratron.

Relays

A relay is an electromagnetically operated remote-control switch. Its main purpose is to switch high-current, high-voltage, or other critical circuits. Since the relay is used almost exclusively to control large amounts of power with relatively small amounts of power, the relay is always a potential source of interference. This is especially true when the relay is used to control an inductive circuit. Relay-actuating circuits should not be overlooked as possible interference sources. Even though the actuating currents are small, the inductances of the actuating coils are usually quite high. It is not unusual for the control circuit of a relay to produce more interference than the controlled circuit.

Thyratrons

A thyratron is a gas-filled, grid-controlled, electronic switching tube used mainly in radar modulators. The current in a thyratron is either ON or OFF; there is no in-between. Since the time required to turn a thyratron ON is only a few microseconds, the current waveform in a thyratron circuit always has a sharp leading edge. As a result, the waveform is rich in radio interference energy. The voltage and peak power in a radar modulator are usually very high; the waveforms are intentionally made as sharp and flat as possible. Although these factors are essential for proper radar operation, they also increase the production of interference energy.

PULSED ELECTRONIC EQUIPMENT

Pulse interference is generated by pulsed electronic equipment. Types of systems that fall within this category include radar, beacons, transponders, and coded-pulse equipment.

Radar

In radar equipment, range resolution depends largely on the sharpness of the leading and trailing edges of the pulse. The ideal pulse is a perfect rectangle. Target definition is also dependent on the narrowness of the pulse. Both the steepness and narrowness of a pulse determine the number and amplitudes of harmonic frequencies. With respect to the shape of a radar pulse, the better the radar is working, the greater the interference it is capable of producing. Most of the interference is produced at frequencies other than those leaving the radar antenna, except in receivers operating within the radar band.

Radar interference at frequencies below the antenna frequency severely affects all receivers in use. Principal sources of such interference are the modulator, pulse cables, and transmitter.

Coded-Pulse Equipment, Beacons, and Transponders

Pulsed electronic equipment also includes IFF, beacons, tacan, teletype, and other coded-pulse equipment. The interference energy produced by this group is the same as that produced by radar-pulsing circuits. The effects of this interference energy are lessened because the equipment is usually self-contained in one shielded case, and uses lower pulse power. The effects are increased because the radiating frequencies are lower; this permits fundamental frequencies and harmonics to fall within frequency bands used by other equipment. Each of these equipments is highly capable of producing interference outside the aircraft where it can be picked up by receiver antennas.

PROPELLER SYSTEMS

Propeller systems, whether hydraulically or electrically operated, are potent generators of radio interference. The sources of interference include propeller pitch control motors and solenoids, governors and associated relays, synchronizers and associated relays, deicing timers and relays, and inverters for selsyn operation.

Propeller control equipment generates clicks and transients as often as 10 per second. The audio frequency envelope of commutator interference varies from about 20 to 1,000 Hz. The propeller deicing timer generates intense impulses at a maximum rate of about four impulses per minute.

Values of current in the propeller system are relatively high; consequently, the interference voltages generated are severe. They are capable of producing moderate interference at frequencies below 100 kHz and at frequencies above 1 MHz. However, the interference voltages can cause severe interference at intermediate frequencies.

RECEIVER OSCILLATORS

Either directly or through frequency multipliers or synthesizers, the local oscillator in a superheterodyne receiver generates an RF signal at a given frequency. The local oscillator signal is mixed with another RF signal to produce an intermediate frequency (IF) signal. Depending on receiver design, the frequency of the local oscillator signal is either above or below the frequency of the RF signal by a frequency equal to the IF.

The amount of interference leaving the receiver through its antenna is roughly proportional to the ratio of the tuned input frequency to the intermediate frequency. For any tuning band on the receiver, oscillator leakage is highest at the low end of the band. Also, the lower the intermediate frequency, the greater the leakage probability.

Although the receiver antenna is the principal outlet of oscillator leakage, leakage can occur from other points. Any path capable of introducing interference into a receiver is also capable of carrying internally generated interference out of the receiver. The paths of entry are discussed more fully later in this chapter.

Oscillator leakage from a single communications receiver in an aircraft is not likely to be a direct source of interference except in a very large aircraft where two or more frequencies in the same band are used simultaneously. However, high-order harmonics of the oscillator frequency can become troublesome in the VHF band and above.

Oscillator leakage from a swept-tuning receiver can produce interference in any receiver aboard the aircraft. This is done directly (on harmonics) or by nonlinear mixing as shown in the following example:

- Receiver A, operating at a frequency of 2100 kHz, with an IF of 500 kHz, has oscillator leakage at 2600 kHz (or 1600 kHz).

- Receiver B, operating at 150 MHz, with an IF of 10 MHz, has oscillator leakage at 160 MHz (or 140 MHz).

- Receiver C, sweeping a frequency band from 200 to 300 MHz, with an IF of 30 MHz, has oscillator leakage across the band 170 to 270 MHz (or 230 to 330 MHz).

Each receiver is capable of interfering with the other receivers at the oscillator frequency and its harmonics. In addition, with the presence of a nonlinear detector, the leakage signals from the three receivers can be mixed and interfere with the following frequencies:

- Receiver A and B, after nonlinear mixing, can produce interference at 160 ± 2.6 MHz.

- Receivers A and C can similarly produce interference at any frequency from 200 ± 2.6 to 300 ± 2.6 MHz; receivers B and C between 200 ± 160 to 300 ± 160 MHz.

NONLINEAR ELEMENTS

A nonlinear element is a conductor or semiconductor whose resistance or impedance varies with the voltage applied across it. Typical examples are metallic oxides, certain nonconducting crystal structures, semiconductor devices, and electron tubes. Nonlinear elements that could cause radio interference in aircraft are overdriven semiconductors and vacuum tubes, oxidized or corroded joints, cold-solder joints, and unsound welds.

In the presence of a strong signal, a nonlinear element acts like a detector or mixer. It produces harmonics and sum and difference frequencies from the signal applied to it. These spurious frequencies are called external cross-modulation. These spurious frequencies (sum, difference, and harmonics) can be expected to cause interference problems when the combined product of their field strengths exceed one millivolt.

A common example of this action is the entry of a strong off-frequency RF voltage into the mixer stage of a superheterodyne receiver. By the time the interfering signal has passed through the preselector stages of the receiver, it has undergone distortion by clipping. Therefore, the interfering signal is essentially a rectangular wave that is rich in harmonics. Frequency components of the wave beat both above and below the local oscillator frequency and its harmonics and produce, at the output of the mixer, signals that are acceptable to the IF amplifier.

POWER LINES

Alternating current power sources have already been briefly discussed as broadband sources of receiver interference. Even though they are conducting a nearly sinusoidal waveform, ac signals on power lines are capable of interfering with audio signals in receivers. In such cases, only the power-line frequency appears. However, where multiple sources of ac power are present, these signals are capable of being mixed in the same manner as discussed under receiver radiation. Sum and difference frequencies appear.

In ac-powered equipment, ac hum can appear at the power frequency or at the rectification ripple frequency. The rectification ripple frequency is twice the power frequency times the number of phases. Normally, aircraft systems use only single- and three-phase sources at a nominal 400 Hz. Full-wave rectification with single-phase 400-Hz power gives a ripple frequency of 800 Hz; a three-phase source yields 2400 Hz. This ripple produces interference varying from annoyance to complete unreliability of equipment, depending upon the severity and its coupling to susceptible elements.

INTERFERENCE COUPLING

Openings in the outer shields of equipment are necessary for the entrance of power leads, control leads, mechanical linkages, ventilation, and antenna leads. Interference entering these openings is amplified by various amounts, depending upon the point of entry into the equipment's circuits. Coupling between the entry path and the sensitive points of the receiver can be in any form.

CONDUCTIVE COUPLING

Interference is often coupled from its source to a receiver by metallic conduction. Normally this is done by way of mutual impedance, as shown in figure 5-1. Note in the figure that A is the power source, B the receiver, and C the interference source. The interference is maximum at the interference source (C) and attenuates rapidly to a relatively low value at battery (A) because of the very low impedance of the battery. It is apparent from the size of the arrows that the nearer the power tap of the receiver (B) to the interference source (C), the greater the amplitude of interfering current in the BC loop.

INDUCTIVE MAGNETIC COUPLING

Every current-carrying conductor is surrounded by a magnetic field whose intensity variations are faithful reproductions of variations in the current in the conductor. When another parallel conductor is cut by the lines of force of this field, the conductor has a current induced into

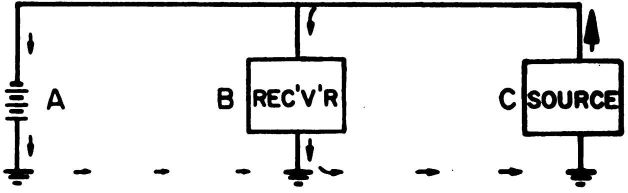

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Figure 5-1.—Path of conducted interference.

it. The amplitude of the induced current depends upon the following factors:

- The strength of the current in the first conductor
- The nearness of the conductors to each other
- The angle between the conductors
- The length through which the conductors are exposed to each other

The amount of the variation in the current that directly affects variation in the magnetic field surrounding the conductor depends upon the nature of the current. When the conductor is a power lead to an electric motor, all the frequencies and amplitudes associated with broadband interference are present in the magnetic field. When the lead is an ac power lead, a strong sinusoidal magnetic field is present. When the lead is carrying switched or pulsed currents, extremely complex broadband variations are present. As the magnetic field cuts across a neighboring conductor, a voltage replica of its variation is induced into the neighboring wire. This causes a current to flow in the neighboring wire. When the neighboring wire leads to a sensitive point in a susceptible receiver, serious interference with that receiver's operation can result. Similarly, a wire carrying a steady pure dc current of high value sets up a magnetic field capable of affecting the operation of equipment whose operation is based upon the earth's magnetic field.

Shielding a conductor against magnetic induction is both difficult and impractical. Nonferrous shielding materials have little or no effect upon a magnetic field. Magnetic shielding that is effective at low frequencies is prohibitively heavy and bulky.

In aircraft wiring, the effect of induction fields should be minimized. This can be done by use of the proper spacing and coupling angle between wires. The degree of magnetic coupling diminishes rapidly with distance. Interference coupling is least when the space between active and passive leads is at a maximum and when the angle between the leads approaches a right angle.

INDUCTIVE-CAPACITIVE COUPLING

Capacitive (electric) fields are voltage fields. Their effects depend upon the amount of capacitance existing between exposed portions of the noisy circuit and the noise-free circuit. The power transfer capabilities are directly proportional to frequency. Thus, high-frequency components are more easily coupled to other circuits. Capacitive coupling is relatively easy to shield out by placing a grounded conducting surface between the interfering source and the susceptible conductor.

COUPLING BY RADIATION

Almost any wire in an aircraft system can, at some particular frequency, begin to act like an antenna through a portion of its length. Inside an airframe, however, this occurs only at very high frequencies. At high frequencies, all internal leads are generally well shielded against pickup of moderate levels of radiated energy. Perhaps the only cases of true inside-the-aircraft radiation at HF and below occur in connection with unshielded or inadequately shielded transmitter antenna leads.

COMPLEX COUPLING

Some examples of interference coupling involve more than one of the types (conduction, induction, or radiation) just discussed. When more than one coupling occurs simultaneously, corrective actions, such as bonding, shielding, or filtering, used to correct one type of coupling can increase the coupling capabilities of another type of coupling. The result may be an increase in the transfer of interference. For example, an unbonded, unfiltered dc motor can transfer interference to a sensitive element by conduction, inductive coupling, capacitive coupling, and by radiation. Some frequencies are transmitted predominately by one form of coupling, and some frequencies by others. At still other frequencies, all methods of transmission are equally effective. On the motor used as an example, bonding almost always eliminates radiation from the motor shell. It also increases the intensity in one of the other methods of transmission, usually by conduction. The external placement of a low-pass filter or a capacitor usually reduces the intensity of conducted interference. At the same time, it may increase the radiation and induction fields. This occurs because to interference voltages, the filter appears to be a low-impedance path across the line. Relatively high interference currents then flow in the loop formed between the source and the filter. For complex coupling problems, multiple solutions may be required to prevent the interference.

RECEIVER INTERFERENCE REDUCTION COMPONENTS

Radio interference reduction at the source may be accomplished to varying degrees by one or more of the following methods: short circuiting, dissipation, open circuiting, or a combination of all three.

Normally, discrete components are used to achieve interference reduction at the source. Capacitors, resistors, and inductors are used to short circuit, dissipate, and open circuit the interference, respectively.

CAPACITORS

Short circuiting interference is done by using capacitors connected across the source. The perfect capacitor looks like an open circuit to dc or the power frequency, and progressively as a short circuit to ac as the frequency is increased.

Function

The function of a capacitor in connection with radio interference filtering is to provide a low-impedance radio-frequency path across the source. When the reactance of the capacitor is lower than the impedance of the power lines to the source, high-frequency voltages see the capacitor as a shorter path to ground. The capacitor charges to the line voltage. It then tends to absorb transient rises in the line voltage and to provide energy for canceling transient drops in the line voltage.

Limitations

The efficiency of a perfect capacitor in bypassing radio interference increases in direct proportion to the frequency of the interfering voltage and in direct proportion to the capacitance of the capacitor. All capacitors have both inductance and resistance. Any lead for connecting the capacitor has inductance and resistance as a direct function of lead length and an inverse function of lead diameter. Some resistance is inherent in the capacitor itself in the form of dielectric leakage. Some inductance is inherent in the capacitor. Inherent inductance is usually proportional to the capacitance.

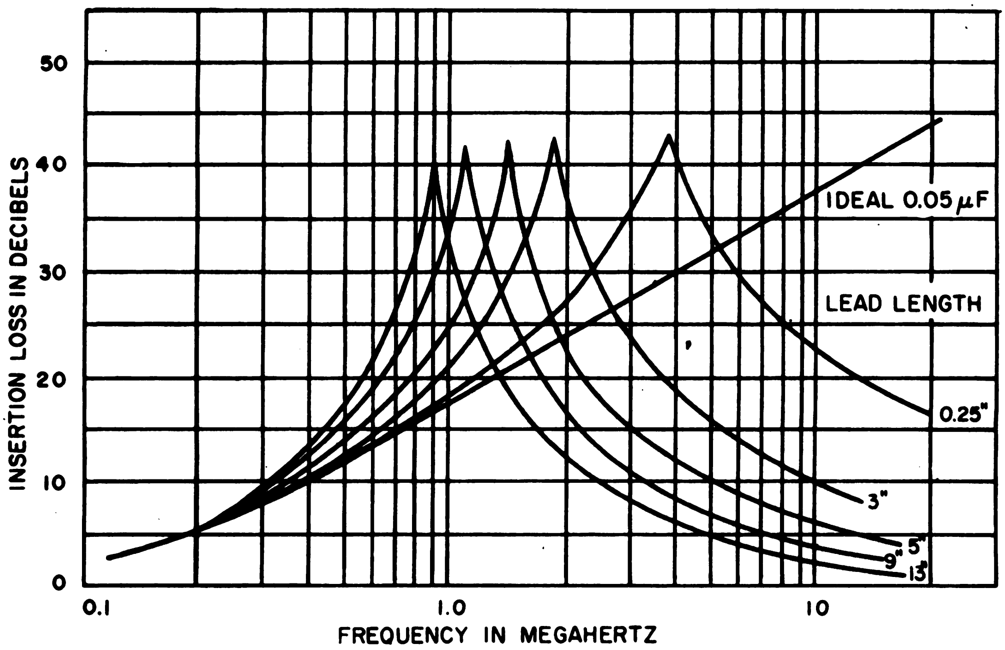

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Figure 5-2.—Crossover frequency of a 0.05-microfarad feedthrough with various lead lengths.

The effect of the inherent resistance in a high-grade capacitor is negligible as far as its filtering action is concerned. The inherent inductance plus the lead inductance seriously affects the frequency range over which the capacitor is useful. The bypass value of a capacitor with inductance in series varies with frequency.

At frequencies where inductive reactance is much less than capacitive reactance, the capacitor looks very much like a pure capacitance. As the frequency approaches a frequency at which the inductive reactance is equal to the capacitive reactance, the net series reactance becomes smaller until the resonant frequency, a point of zero impedance, is reached. At this point, maximum bypass action occurs. At frequencies above the resonant frequency, the inductive reactance becomes greater than the capacitive reactance. The capacitor then exhibits a net inductive reactance whose value increases with frequency. At frequencies much higher than the resonant frequency, the value of the capacitor as a bypass becomes lost.

The frequency at which the reversal of reactance occurs is controlled by the size of the capacitor and the length of the leads. For instance, the installation of a very large capacitor frequently requires the use of long leads. As an example of the influence of lead length upon the bypass value of a capacitor, the following data is presented for a typical 4-microfarad capacitor whose inherent inductance is 0.0129 henrys:

Lead Length	Crossover Frequency
1″	0.47 MHz
2″	0.41 MHz
3″	0.34 MHz
4″	0.30 MHz
6″	0.25 MHz

Note that for a 4-μF capacitor, each additional inch of lead causes the capacitance-inductance crossover point to be reduced by about 10 percent.

Refer to figure 5-2. Notice the capacitance-to-inductance crossover frequencies for various lead lengths of a 0.05-μF capacitor. Also, notice the difference in the crossover frequencies for the 3-inch lead for the 4-μF capacitor discussed above and for the 3-inch lead for the 0.05-μF capacitor in the figure.

Coaxial Feedthrough Capacitors

Coaxial feedthrough capacitors are available with capacitances from 0.00005 to about 2 μF. These capacitors work well up to frequencies several times those at which capacitors with leads become useless.

The curves in figure 5-3 compare the bypass value of a feedthrough capacitor of 0.05 μF with

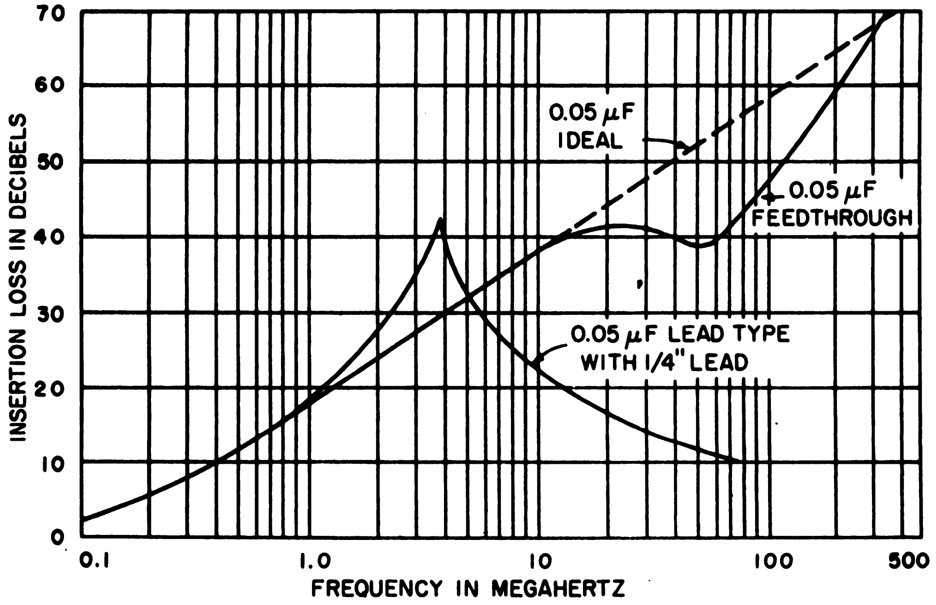

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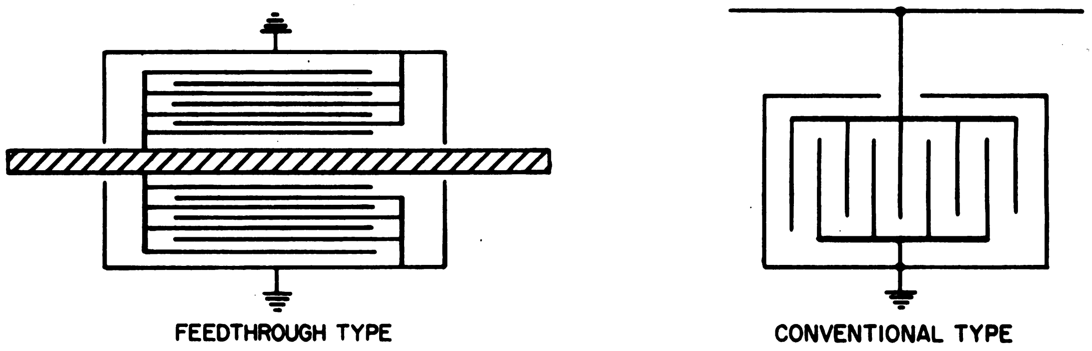
Figure 5-3.—Crossover frequency of a 0.05-microfarad feedthrough capacitor.



FEEDTHROUGH TYPE

CONVENTIONAL TYPE

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Figure 5-4.—Internal construction of feedthrough and conventional capacitors.

that of a hypothetically perfect capacitor of the same capacitance. The feedthrough capacitor differs from the capacitor with leads in that the feedthrough capacitor type forms a part of both the circuit being filtered and the shield used to isolate the filtered source. Lead length has been reduced to zero. The center conductor of the feedthrough capacitor must carry all the current of the filtered source and must have an adequate current rating to ensure against dc loss or power frequency insertion loss. The internal constructions of feedthrough and conventional capacitors are shown in figure 5-4. Notice the differences in the two types.

Selection of Capacitors

Capacitors used for filtering circuits in aircraft should be selected for characteristics such as physical size, high temperature and humidity tolerances, and physical ruggedness. The capacitors should have an adequate voltage rating (at least twice that of the circuit to be filtered), and should be installed with minimum lead length.

Application of Capacitive Filters

Every circuit carrying an unintentionally varying voltage or current capable of causing radio interference should be bypassed to ground by suitable capacitors. When the nature of the variations are such that interference is caused at both high and low frequencies, a capacitor should be chosen and installed to provide an adequate insertion loss at the lowest frequency where interference exists. When the overall capacitance required at low frequency provides inadequate insertion loss at high frequencies, it should be bridged in the shortest and most direct manner possible by a second capacitor.

A capacitive filter should be installed as near as possible to the actual source of interference. Lead length should be held to an absolute minimum for two reasons. First, the lead to the capacitor carries interference that must not be allowed to radiate. Second, the lead has inductance that tends to lower the maximum frequency for which the capacitor is an effective bypass.

To the extent possible, a filter capacitor should be installed to make use of any element of the filtered circuit that provides a better filtering action. Figures 5-5, 5-6, and 5-7 illustrate proper use of filter capacitors.

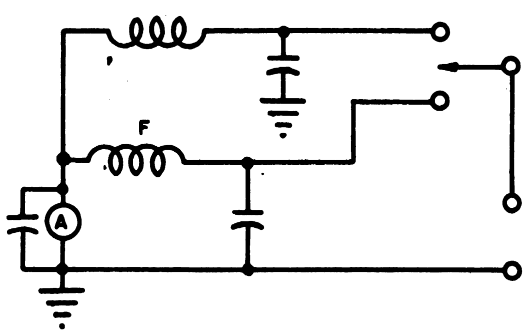

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Figure 5-5.—Capacitive filtering of a reversible dc series motor.

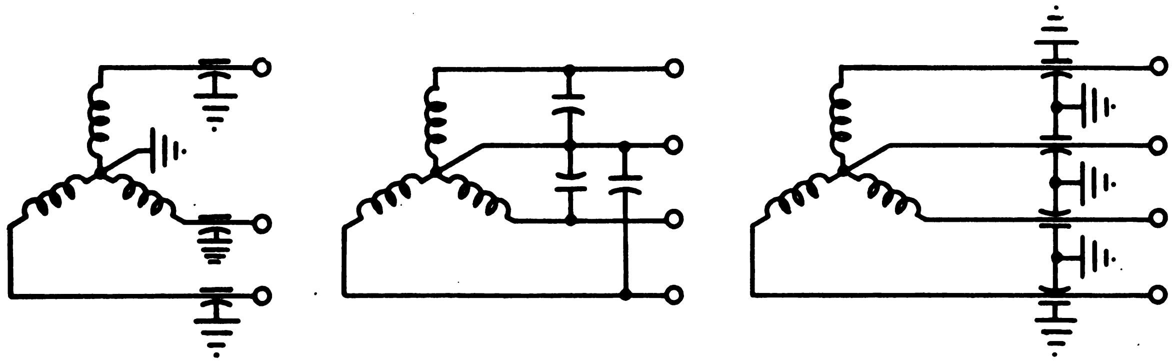

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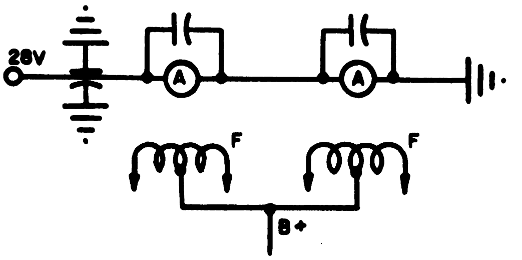
Figure 5-6.—Capacitive filtering of a three-phase alternator.



223.258

Figure 5-7.—Capacitive filtering of a servomotor.

Capacitive Filtering in an Ac Circuit

The radio interference generated in slip-ring ac motors and generators is a transient caused by sliding contacts plus high-frequency energy from other internal sources. For this reason, filtering should be aimed at reducing high- and very-high frequency noise components with the use of low-capacitance, high-grade capacitors. Wherever possible, feedthrough capacitors should be used. Capacitances should be chosen low enough in value to represent a high impedance at the power frequency and to avoid resonance with the internal inductances of the filtered unit. Voltage ratings should be at least twice the peak voltage across the capacitors.

In a 4-wire electrical system, the neutral lead carries all three phases, and a large quantity of the third harmonic of the power frequency is present. This frequency must be considered in setting capacitance limits and in filtering the return lead. Normal values of capacitance for filtering 400-Hz leads vary from 0.05 to 0.1 microfarad.

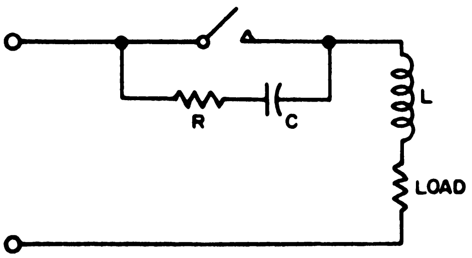
Capacitive Filtering of Switching Devices

Normally, a capacitor should not be used by itself as a filter on a switch in a dc system. In the open position, the capacitor bridging the switch assumes a charge equal to the line voltage. When the switch closes, the capacitor discharges at such a rapid rate that it generates a transient whose interference value exceeds that caused by the opening of the unfiltered circuit. The capacitor across a switch should have enough series resistance to provide a slow discharge when the capacitor is shorted by the switch.

RESISTANCE-CAPACITANCE FILTERS

A resistance-capacitance (RC) filter is an effective arc and transient absorber. The RC filter reduces interference in two ways—by changing the waveform of transients and by dissipating transient energy. Figure 5-8 shows how an RC filter is connected across a switch.

Without the RC filter, the voltage appearing across the switch at the instant the switch is



223.259

Figure 5-8.—An RC filter connected across a switch.

opened is equal to the sum of the line voltage and an inductive voltage of the same polarity. The amplitude of the inductive surge depends upon the inductance of the line and the amplitude of the closed-circuit current.

When the sum of the voltages appearing across the switch is great enough, arcing occurs. When the capacitance is large enough, the capacitor absorbs sufficient transient energy to reduce the voltage to below arcing value. During the charging time of the capacitor, the resistor is passing current and dissipating some of the transient energy.

For maximum absorption of the circuit opening transients, resistance should be small and capacitance should be large. Good representative values are R = 1/5 load resistance and C = 0.25 μF.

Figure 5-9 shows two RC filters used to absorb the transient interference resulting from the opening of a relay field. In circuit A, the value of R_a should be low enough to provide a resistance path to ground less than the line impedance and high enough to lower the Q sufficiently. The capacitor should be at least 0.25 μF with a voltage rating several times the line voltage. Circuit B has the advantages of reducing the capacitor and coil leads to absolute minimum and reducing the relay field current. It also has the disadvantage of carrying the dc coil current. Normal values of each resistance (R_b) in circuit B are 5 percent of the dc resistance of the coil. The capacitor is normally 0.25 μF. Circuit B serves as both a damping load and a high-loss transmission line.

INDUCTANCE-CAPACITANCE FILTERS

Filtering radio interference is done by means of an inductor inserted in series with the ac power source. The inductor offers negligible impedance to the ac or power-line frequency and an increasingly high impedance to transient interference as frequency is increased. Combinations of inductance and capacitance are widely used to reduce both broadband and narrow-band interference.

Filters used to reduce radio interference transmissions are available in the Navy supply system. The filters come in a large variety of types and sizes. Filters are classified as to their frequency characteristics; namely, low-pass, high-pass, bandpass, and band-reject filters.

Filters are also classified as to their applications; namely, power-line, antenna, and audio filters. The type most often used in aircraft is the low-pass power-line filter.

Low-Pass Filters

A low-pass filter is used in an aircraft to filter power leads coming from interference sources. The filter prevents the transmission of interference voltages into the wiring harness and blocks transmission or reception of radio-frequency energy above a specified frequency.

The ideal low-pass filter has no insertion loss at frequencies below its cutoff frequency, but has an infinite insertion loss at all higher frequencies. Practical filters fall short of the ideal in three ways. First, a filter of acceptable physical size and weight has some insertion loss, even under dc conditions. Second, because of the lack of a pure inductor, the transition from low to high impedance is gradual instead of abrupt. Third, the impedance is held to a finite value for the same reason. Figure 5-10 compares the insertion loss of a typical low-pass filter with that of the hypothetical ideal filter.

Figure 5-11 shows the arrangement and typical parameters of a low-pass filter having a design cutoff frequency of 100 kHz. Inductor L must carry load current. It must be wound of wire large enough that its dc insertion loss is negligible.

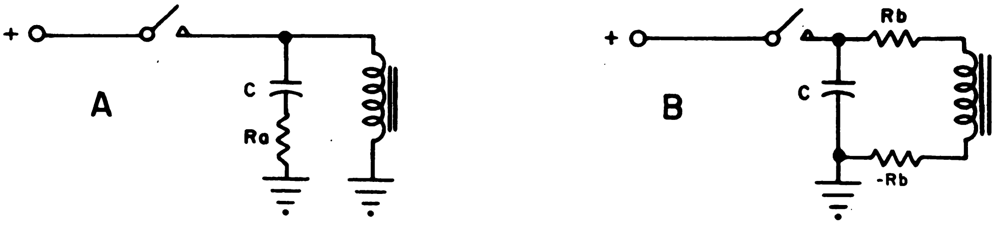


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Figure 5-9.—Methods for using RC filters in relay circuits.

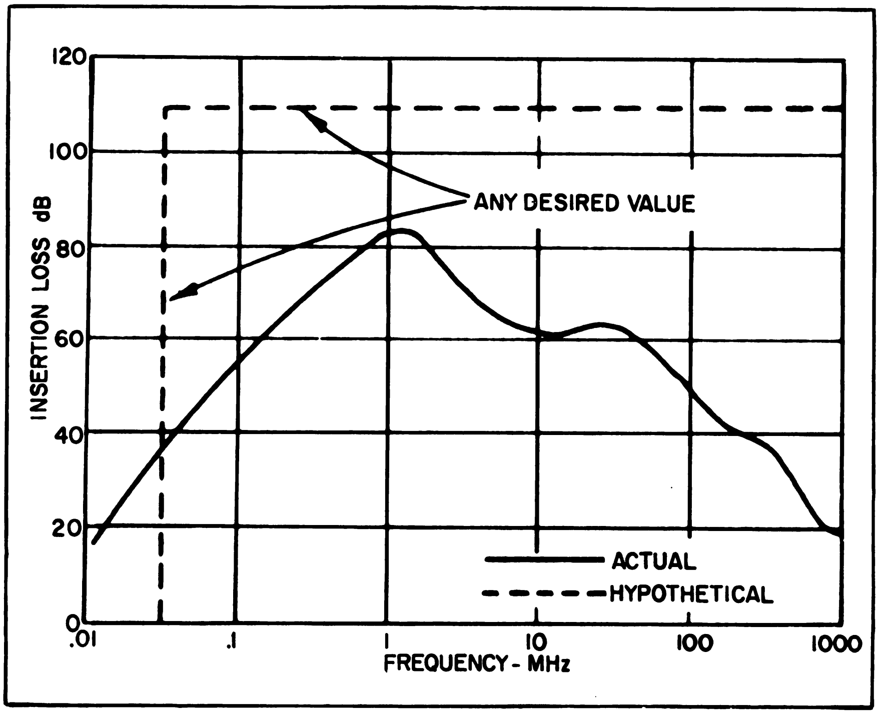

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Figure 5-10.—Insertion loss curve of a commercial low-pass power-line filter.

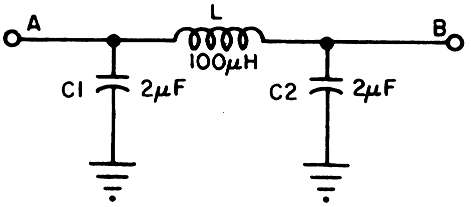

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Figure 5-11.—Low-pass filter circuit.

Therefore, filters are rated as to maximum current. The capacitors C1 and C2 must withstand the line voltage. Therefore, filters are also rated as to maximum voltage.

At frequencies immediately below cutoff, the filter looks capacitive to both the generator and the load. Inductive reactance X_L has little influence and no filtering action takes place. However, at frequencies above cutoff, the series reactance of coil L becomes increasingly higher. The series reactance of coil L is limited only by the resistance of the coil and its distributed capacitance. Coil L then functions as a high-frequency disconnect. The bypass values of both C1 and C2 become increasingly higher and are limited only by the inductance of the capacitors and their leads. As a result of these two actions, high-frequency isolation between points A and B is achieved.

High-Pass Filters

In almost all radio transmitters operating at high frequencies (HF) and above, the master oscillator signal is generated at a submultiple of the output frequency. By use of one or more frequency multipliers, the basic oscillator frequency is raised to the desired output frequency. At the input to the antenna, an overdriven output amplifier may output the output frequency and harmonics of the output frequency. A high-pass filter is very effective in preventing the undesired harmonics from reaching the antenna and being radiated.

High-pass filters are also useful for isolating a high-frequency receiver from the influence of energy of signals of lower frequencies.

Figure 5-12 shows a typical high-pass filter being used to reduce radio-noise interference. In symmetrical high-pass filter sections ($Z_{in} = Z_{out}$), the series combination of C1 and L should resonate at $\sqrt{2}$ times the desired cutoff frequency. The L/C ratio that is chosen should have a square root equal to the terminal impedance.

Bandpass Filters

Bandpass filters provide a very high impedance above and below a desired band of frequencies and a very low impedance to frequencies within that band. Bandpass filters find their greatest application in (1) decoupling the receiver from shock and overload by transmitters operating above and below the receiver pass band and (2) multiplexing or decoupling two or more receivers or transmitters using the same antenna.

A bandpass filter can be one of many forms and configurations, depending upon its application. For filtering antennas, a bandpass filter normally consists of one or more high-pass filter sections followed by one or more low-pass filter sections. The configuration of sections is normally selected so the upper limit of the pass band approaches or exceeds twice the frequency of the lower limit of the pass band. Figure 5-13 shows typical arrangements for bandpass filters.

Band-Rejection Filters

A band-rejection (band-stop) filter is used where it is desired to reject or block a band of frequencies from being passed. This filter allows all frequencies above and below this band to be passed with little or no attenuation.

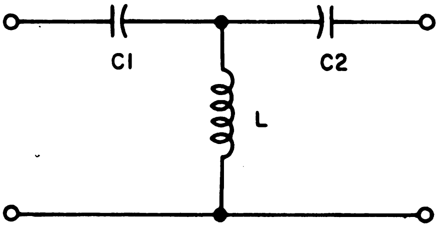

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Figure 5-12.—Schematic diagram of a high-pass filter section.

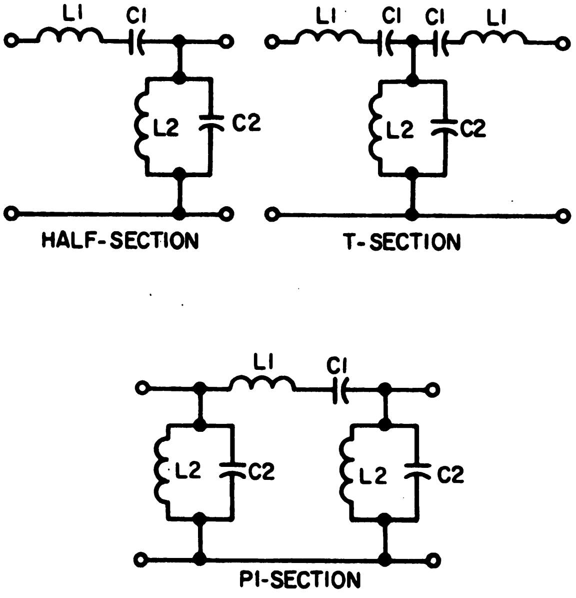

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Figure 5-13.—Examples of bandpass filter circuits.

The band-stop filter circuit consists of inductive and capacitive networks combined and connected to form a definite frequency response characteristic. The band-stop filter is designed to attenuate a specific frequency band and to permit the passage of all frequencies not within this specific band. The frequency range over which attenuation or poor transmission of signals occurs is called the attenuation band and the frequency range over which the passage of signals readily occurs is called the bandpass. The lowest frequency at which the attenuation of a signal starts to increase rapidly is known as the lower cutoff frequency (f_1). The highest frequency at which the attenuation of a signal starts to increase rapidly is known as the upper cutoff frequency (f_2). The basic configurations into which the band-reject filter elements can be arranged or assembled are known as the L- or half-section, the T-section, and the Pi-section configurations. (See fig. 5-14.) For a more in-depth discussion on the various filters discussed in this chapter, you should refer to NAVSHIPS 0967-000-0120, Section 4.

BONDING

Aircraft electrical bonding is defined as the process of obtaining the necessary electrical

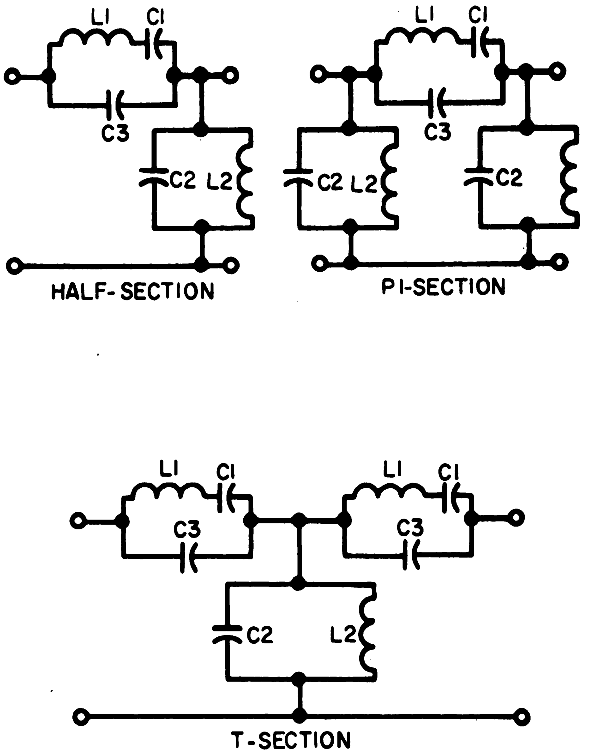

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Figure 5-14.—Examples of band-reject filter circuits.

conductivity between all of the component metallic parts of the aircraft. Bonding successfully brings all items of empennage and internal conducting objects to essentially the same dc voltage level appearing on the basic structure of the fuselage. However, bonding for radio frequencies is not quite so simple. Only direct bonding between affected components can accomplish the desired results at all frequencies. Only when direct bonding is impossible or operationally impracticable should bonding jumpers be used. Regardless of its dc resistance, any length of conductor has inductive reactance that increases directly with frequency. At a frequency for which the length of a bond is a quarter wavelength, the bond becomes a high impedance. The impedance of such a resonant lead becomes greater without limit as the dc resistance becomes lower. Multiple bonding using the same length of bonding jumper increases the impedance at the resonant frequency, but also tends to sharpen the high-impedance area around the resonant frequency. This sharpening is done by the rapid fall of impedance on each side of resonance.

PURPOSES OF BONDING

Bonding must be designed and executed to obtain the following results:

- Protect the aircraft and personnel from hazards associated with lightning discharges

- Provide power-current and fault-current return paths

- Provide sufficient homogeneity and stability of conductivity for RF currents affecting transmission and reception

- Prevent development of ac potentials on conducting frames, enclosures, cables of electrical and electronic equipment, and on conducting objects adjacent to unshielded transmitting antenna lead-ins

- Protect personnel from the shock hazard resulting from equipment that experiences an internal power failure

- Prevent the accumulation of static charges that could produce radio interference or be an explosion hazard due to periodic spark discharge

BONDING FOR LIGHTNING PROTECTION

Close-riveted skin construction that divides any lightning current over a number of rivets is considered adequately bonded to provide a lightning discharge current path. Control surfaces and flaps should have a bonding jumper across each hinge. To protect the control cables and levers, additional jumpers should be connected between the control surface and the structure. The length of a discharge path through the control system should be at least ten times the length of the path of the jumper or jumpers.

All external electrically isolated conducting objects (except antennas) should have a bonding jumper to the aircraft skin or structure. To ensure a low-impedance path so the voltage drop developed across the jumper systems by the lightning discharge is minimized, bonding jumpers must be kept as short as possible. When practicable a bonding jumper should not exceed 3 inches.

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